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QUANTIFICATION OF ELECTRONIC CIRCUIT CONNECTION TECHNIQUES

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FOREWORD

This report was prepared by Hughes Aircraft Company, Ground Systems Group, Fullerton, California. The research team was headed by R. E. Schafer and W. Yurkowsky. Other contributors were K. R. Brock, Dr. H. Ellithorn and J. R. Shackleton. The study was performed for the Research and Technology Division of Rome Air Development Center under Contract Number AF 30 (602) -3177. Mr. Donald Fulton was the RADC Project Manager.

The researchers wish to acknowledge the assistance and cooperation of Mr. Fulton throughout the effort.

The study was made possible by the submission of reliability reports by many individuals within Hughes Aircraft Company and numerous others in organizations throughout the United States and Great Britain. The organizations which contributed failure rate data are listed separately under Acknowledgements.

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ABSTRACT

This study is directed toward gathering reliability data on several presently used electronic circuit connection types. Laboratory and field reliability reports were gathered from known producers and users of electronic equipment. A restriction was placed on the study that no data from controlled tests were generated during the study period. The study was conducted during the period from July through December of 1963.

In all, data for 350 billions of connection operating hours were collected during the six month study. The data covered 6 types of connections: solder, resistance welding, wire wrap, crimp, ultrasonic welding, and thermal compression bonding. The number of operating hours was small and no failures were noted in the reports obtained on the latter two types of connections. The remainder of the study, therefore, was concentrated on the four connection types on which sufficient data were available.

Failure rates and confidence intervals were calculated and compared for each of the four connection types. These were based on the general types of equipments from which the reliability reports were collected. Additional calculations were based on the laboratory reliability test reports.

Mathematical analyses were performed on the data collected in an attempt to measure the effects of environmental stresses on connection failure rates. The details of these analyses and their results are fully described.

A merit index was developed so that designers may select optimum types of connections for use in various applications. The details of factor and subfactor selection and their quantification are described. Application weights for several classes of Air Force ground equipments are developed and presented. The use of the Merit Index is demonstrated through the presentation of four examples.

PUBLICATION REVIEW

This report has been reviewed and is approved. For further technical information on this project, contact Mr. Donald W. Fulton, EMERR, Ext 5264.

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Burroughs Corporation, Pasadena, California

The Sippican Corporation, Marion, Massachusetts

Engineered Electronics Company, Santa Ana, California

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CTS of Berne, Incorporated, Berne, Indiana

North American Aviation, Incorporated, Autonetics, Anaheim, California

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The Boeing Company, Seattle, Washington

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SECTION 1 - INTRODUCTION

The life characteristics of electronic equipments are highly dependent on the reliability of the type of connection used. For every electronic part in a piece of equipment, there are approximately five connections. And yet, a review shows that most designers' reliability handbooks contain failure rate data on every conceivable part except electronic circuit connections. This is probably because few people have troubled themselves with compiling reliability and environmental data on connections. In the case of the type of connection, there are many decision factors which the designer must consider in addition to the reliability characteristics. The importance of these factors varies with the end use of the equipment. Therefore, some systematic tool is needed by the designer to ensure that he considers all factors when selecting a connection for use in a given equipment for a given application.

This study, therefore, focuses attention on the problems of the designer in the selection of an optimum connection type by working toward the following objectives:

- Obtain estimates of the failure rates of various connection techniques through the analysis of laboratory test reports and equipment operation reports.

- Determine the effects of environment on the failure rates of the connection types of interest.

- Develop a merit index for connections that allows the quantification of the decision factors that the designer must consider when selecting a connection for use in a given application

SUMMARY OF SECTION 2

The connection failure rate data contained in this report were obtained by the following methods: a literature search, a letter survey, a search of unpublished data in the Hughes Aircraft Company files, and by personal contacts. Sufficient data were gathered to calculate failure rates for solder, resistance weld, crimp, and wire wrap (see Table 2-1). The failure rates are based on the data from equipment only. No laboratory test reports were combined with field data. The data are divided into groups based upon the type of equipments or the type of laboratory tests in which the various types of connections were used. Failure rates are computed for these groups (see Tables 2-4 to 2-6). The variation in the failure rates of the connection seems to vary with the type of equipment in which it is used. These effects of equipment type on connection failure rate are compared to typical reliability handbook "K" factors in Table 2-7. The calculated failure rates raised several interesting questions. When their magnitudes are compared to typical handbook failure rates it appears that the connection failure rates are higher than should be expected. When it is considered that many connection repairs are so minor that the technician fails to report them, it would appear that the calculated connection failure rates are lower than should be expected. This is an example of the problems encountered when analyzing the reliability data gathered during the study. The latter part of the section outlines the assumptions and ground rules used in gathering and in analyzing the data.

SECTION 2-DATA COLLECTION AND ANALYSIS

2.1 Data Search

The search for data on connections consisted of four parts: a literature search, a letter survey, a search of company files, and a survey employing personal contacts.

The literature search was conducted to obtain published data on connections. The search was concerned with obtaining performance information for the Merit Index, as well as failure rate information for the analysis. A bibliography of 275 articles of interest was compiled from the following sources:

- The Engineering Index
- U.S. Government Research Reports
- NASA Index
- Pacific Aeronautical Library Index
- Jet Propulsion Laboratory Abstracts
- Hughes Aircraft Company Document Index
- Hughes Aircraft Company Report Index
- FARADA Files
- IDEP Files
- ECRC Report Index
- DDC Document Lists

The letter survey was conducted to obtain unpublished data and data contained in the files and the internal reports of the companies contacted. The results of this survey were very disappointing, of over 400 letters sent, less than 3 percent of the recipients replied with useful reliability reports.

A thorough search was also made of the unpublished data in the Hughes Aircraft Company files. This included the following sources:

- Field logs on equipment and systems.
- Laboratory test reports on equipment.
- Data from programs and experiments currently in progress.

The program of personal contacts was by far the most effective data collection medium. Over 75 percent of the information gathered was obtained in this manner. The reason for its success relative to other techniques is that the personal contact permitted a better explanation of program objectives and the nature of the data required.

Over 208 reliability reports on connections were obtained through the data search. Approximately 25 percent of these reports are from Hughes Aircraft Company files. Approximately 350 billion hours of connection operation were gathered for the six connection types. The details of this data are contained in Appendix I.

All of the data contained in this report was gathered by the four data search methods described. No data were generated by controlled laboratory testing, since this was beyond the scope of the study. The manner in which the data were obtained created some difficulties. The study reveals that

little documentation is being done on connection failure rates. In several cases, many hours of operating time were rendered useless when it was revealed that all failures were reported in the logs except connections. Frequent answers to requests for information were that these data were not available without further time consuming searching (which all sources were unwilling to do), or the data was considered proprietary.

2.2 Failure Rate Estimates

One of the primary objectives of the study was to determine the failure rate of various types of connections. The following types of connections were investigated: solder, resistance weld, wire wrap, crimp, ultrasonic weld, thermal compression bond, conductive adhesive, gold foil, and gallium alloy. No quantitative data were found on the last three types of connections.

For the other types of connections studied the failure rates were calculated by dividing the joint-hours of operation by the number of failures. Where no failures were observed only a confidence interval could be calculated. Justification of this method of calculating failure rates is presented in Appendix V.

To perform an analysis on the data, the data were grouped into two classifications: data that came from laboratory tests on components, modules and connections and data that came from reports on operating equipment. This grouping appeared to be a reasonable first step in assembling the data for analysis, since the desired failure rates are those rates which most closely reflect the natural failure rate of connections. The desired rates, therefore, are obtained from the latter classification. Laboratory tests by their very nature seldom allow connections to fail in a natural fashion. Failures in laboratory tests are generally induced by acceleration techniques. The relationship between connection failures observed in operating equipment is presently not known. The results of the analysis performed on the data from laboratory tests is discussed below in terms of each specific type of connection.

Table 2-1 presents the failure rates by connection type. The data from equipment reports indicates an extremely low failure rate for a wire wrap connection and a relatively high failure rate for a crimp connection. No quantitative information was received on conductive adhesive, gold foil, and gallium alloy types of connections. No equipment reports were received which provided data on ultrasonic weld and thermal compression bond connection types.

An inspection test of the confidence intervals shown in Table 2-1 will suffice to show any statistically significant differences between the failure rates of the connection types. The test determines whether a confidence interval for one failure rate is wholly contained within the confidence interval of another failure rate. If the test turns out true, no statistically significant difference exists. Conversely, if the intervals are mutually exclusive, a statistically significant difference exists. No conclusions can be drawn where partial overlap of confidence intervals is found. By inspection of Table 2-1 the following statements can be made. No statistically significant difference exists between the failure rates for solder and resistance welding. A statistically significant difference does exist, however, between the failure rates for wire wrap and each of the other three connection types. A statistically significant difference exists between the failure rates for solder and crimp. No conclusion can be drawn by inspection of the confidence intervals

TABLE 2-1

FAILURE RATES BY CONNECTION TYPE*

Connection Type	Failure Rate (%/1000 hrs)	90% Confidence Interval (%/1000 hrs)	No. of Failures	No. of Joint-Hrs. Operation x 10^8
Wire Wrap	0.00000037	0.00000020 - 0.0000011	1	2705.05
Solder	0.00057	0.00053 - 0.00062	427	748.46
Resistance Welding	0.00070	0.00035 - 0.0011	8	11.476
Crimp	0.0016	0.00070 - 0.0028	6	3.73

*These failure rate data are based upon data from equipment reports. The data from reports on laboratory tests are not included.

for the failure rates of resistance welding and crimp. To determine significance for the latter case a special F test was developed. Table 2-2 presents the results of the "F" test of significance at the 0.1 level. The results show no significant difference between the failure rates for resistance welding and crimp. It is assumed in both the determination of the confidence interval and the development of the "F" test that the observed failure rates are constant with time. It was beyond the scope of the study to validate this assumption because of the character of the observed data. Details of the development of the "F" test are contained in Appendix III.

The data contained in Table 2-1 is a summary of the data contained in Tables 2-3 through 2-6. Each of the latter tables presents a breakdown of the failure rates for a specific connection type: solder, resistance weld, wire wrap, and crimp. Since no failures were contained in the 0.328×10^6 joint-hours (connections times hours of operation) of laboratory test data for ultrasonic weld and the 510×10^6 joint-hours of laboratory test data for thermal compression bond, no point estimates of failure rates could be calculated. The latter data is tabulated in Appendix I.

Table 2-3, presents the solder connection failure rates. The data is categorized by the type of report from which the data was obtained. The definitions for the first column, Type of Data, is contained in Appendix I. It became apparent that there were additional sub-classes into which the data from the various reports should be categorized. Large amounts of data from equipment operation reports were collected that contained no observed failures. Rather than eliminate the large number of joint-hours this data represented, the data was grouped according to the type of equipment from which it was obtained. The sub-classification employed follows a pattern of increasing vibration stress to be expected on each type of equipment. The term, mobile, used in the definitions in Appendix I applies to Hughes equipment designed for mobile use, but which has been operated, so far, in stationary installations. The data obtained from all space-missile-airborne equipment reports has been grouped together because of the paucity of data in those areas. Reports on space equipment were received for one connection type only, resistance weld.

The data on solder connections contained on Table 2-3 indicates many more observed failures (927) than the data for any other type of connection. As a result of the large number of failures, solder has a very narrow confidence interval and a statistically good failure rate estimate.

It is also interesting to note that over half the observed failures were received in reports on laboratory tests. This undoubtedly is a reflection on the wide use of accelerated test techniques currently employed. No relation was found between the laboratory derived failure rates and the failure rates obtained from the equipment operation reports.

Since the bulk of the data received was on solder connections, it is expected that failure rates for solder connections will appear in seven of the eight sub-classifications. With respect to the data received from equipment reports, it is interesting to note the order by failure rate shown in Table 2-3. The order of increasing connection failure rate seems to coincide with component and equipment failure rates.

TABLE 2-2. "F" TESTS OF SIGNIFICANCE AT THE 0.1 LEVEL

	Wire Wrap	Solder	Resistance Welding	Crimp
Wire Wrap	-	-	-	-
Solder	Significant difference	-	-	-
Resistance Welding	Significant difference	no significant difference	-	-
Crimp	Significant difference	Significant difference	no significant difference	

TABLE 2-3 SOLDER CONNECTION FAILURE RATES

Type of Data	Failure Rate (%/1000 hrs)	90% Confidence Interval (%/1000 hrs)	No. of Joint-Hrs Operation $\times 10^8$	No. of Failures
1. Ground Computers	0.00040	0.00035-0.00044	521.3	207
2. General Ground Equipment	0.00057	0.00048-0.00067	179.5	102
3. Shipboard Equipment	0.00085	0.00052-0.0013	16.4	14
4. Ground Radar	0.0014	0.00025-0.0034	1.4	2
5. Airborne Equipment	0.0034	0.00029-0.040	29.86	102
EQUIPMENT TOTAL	0.00057	0.00053-0.00062	748.46	427
6. Laboratory Tests - Vacuum Tubes	No Data	No Data	No Data	No Data
7. Laboratory Tests - Connections	0.010	0.00053-0.031	0.0972	1
8. Laboratory Tests - Modules, Parts, and Cards	0.027	0.025-0.029	18.39	499
LABORATORY TEST TOTAL	0.027	0.025-0.029	18.49	500

TABLE 2-4 RESISTANCE WELD CONNECTION FAILURE RATES

Type of Data	Failure Rate (%/1000 hrs)	90% Confidence Interval (%/1000 hrs)	No. of Joint - Hrs. Operation x 10^8	No. of Failures
1. Ground Computers	No Data	No Data	No Data	No Data
2. General Ground Equipment	0.00019	0.000033-0.00044	10.72	2
3. Shipboard Equipment	No Data	No Data	No Data	No Data
4. Ground Radar	No Data	No Data	No Data	No Data
5. Airborne Equipment	0.0079	0.0035-0.014	0.756	6
EQUIPMENT TOTAL	0.00070	0.00035-0.0011	11.476	8
6. Laboratory Tests - Vacuum Tubes	0.0018	0.00050-0.0038	1.64	3
7. Laboratory Tests - Connections	No Data	No Data	No Data	No Data
8. Laboratory Tests - Modules, Parts, and Cards	0.038	0.023-0.056	0.372	14
LABORATORY TEST TOTAL	0.0084	0.0054-0.012	2.012	17

TABLE 2-5 WIRE WRAP CONNECTION FAILURE RATES

Type of Data	Failure Rate (%/1000 hrs)	90% Confidence Interval (%/1000 hours)	No. of Joint-Hrs. Operation x 10^8	No. of Failures
1. Ground Computers	0.00000037	0.000000017-0.0000011	2704.55	1
2. General Ground Equipment	No Data	No Data	No Data	No Data
3. Shipboard Equipment	No Data	No Data	No Data	No Data
4. Ground Radar	No Data	No Data	No Data	No Data
5. Airborne Equipment	-	0-0.0046	0.5	0
EQUIPMENT TOTAL	0.00000037	0.000000020-0.0000011	2705.05	1
6. Laboratory Tests - Vacuum Tubes	No Data	No Data	No Data	No Data
7. Laboratory Tests - Connections	0.45	0.33 - 0.59	0.0684	31
8. Laboratory Tests - Modules, Parts, and Cards	No Data	No Data	No Data	No Data
LABORATORY TEST TOTAL	0.45	0.33 - 0.59	0.0684	31

TABLE 2-6 CRIMP CONNECTION FAILURE RATES

Type of Data	Failure Rate (%/1000 hrs)	90% Confidence Interval (%/1000 hrs)	No. of Joint-Hrs. Operation x 10^8	No. of Failures
1. Ground Computers	0.0016	0.00070-0.0028	3.73	6
2. General Ground Equipment	No Data	No Data	No Data	No Data
3. Shipboard Equipment	No Data	No Data	No Data	No Data
4. Ground Radar	No Data	No Data	No Data	No Data
5. Airborne Equipment	*	*	*	*
EQUIPMENT TOTAL	0.0016	0.00070-0.0028	3.73	6
6. Laboratory Tests - Vacuum Tubes	No Data	No Data	No Data	No Data
7. Laboratory Tests - Connections	-	0-20	0.00012	0
8. Laboratory Tests - Modules, Parts, and Cards	No Data	No Data	No Data	No Data
LABORATORY TESTS TOTAL	-	0-20	0.00012	0

* 0.00087%/1000 hour quoted with no quantitative back-up data. Additional information contained in Appendix.

Table 2-7 presents this information to show the graduation observed for the increase in the failure rates of solder connections between ground computer reports and airborne reports when compared to the K-factor measure of environmental stress.

The 53 reliability reports obtained on resistance welded connections were combined into the equipment classes previously mentioned. Failure rates and confidence intervals were calculated and these are shown in Table 2-4. Only General Ground Equipments and Airborne reliability reports were received on field equipment application classes. Although only a small number of failures were observed, the expected higher failure rate for Airborne Equipment is observed. Forty-one of the fifty-three reports on resistance welding were concerned with laboratory tests. Also, the overwhelming majority of these were from only two sources. These particular laboratory tests were definitely performed under severe environmental stresses. The indication is given that the induced stresses resulted in a materially higher failure rate.

As in the case of welded connections, the greatest number of wire wrap reliability reports obtained were based on laboratory tests. Thirty-one of the 35 reports were of this type. It can be noted from Table 2-5 that the combined failure rate from these laboratory tests was 0.45°/o/1000 hours. This failure rate is not indicative of the expected field performance. They were performed under severe environmental conditions with fewer than the specified number of wraps around the terminal. Perhaps the most important failure rate calculated in the entire study is shown on Table 2-5. This rate is for wire wrap connections on Ground Computers. The calculated failure rate is 0.000000037°/o/1000 hours. It is interesting to note that this calculation is based on only one observed failure in a total of 270 billion joint-hours of field operation. This is a tremendous amount of operating time when compared with the other reliability reports received. These hours were received in only three reports. Two of the reports had nearly identical amounts of joint-hours (approximately 135 billion joint-hours each). One of the two reports contained one failure observation while the other contained none. It was at first suspected that perhaps duplicate reports had been received since the operating hours were so similar. However, subsequent investigation indicated that these were in fact different sets of observations. It may be said, therefore, that since only one failure has been observed on wire wrap field data that knowledge regarding the true failure of this type of connection is scant. In spite of this, it would appear reasonable to suggest that the failure rate of wire wrap is quite small.

Table 2-6 summarizes the data obtained and the failure rates calculated for crimp connections. Eleven reliability reports were combined to obtain the Ground Computers failure rate of 0.0016°/o/1000 hours. The magnitude of this failure rate however, seems doubtful. The reasons for this statement are two-fold: First, it was noted that the reports represented qualification tests, quality assurance acceptance tests, and operating hours during debugging. Second, one reliability report gave their failure rate as 0.00087°/o/1000 hours without any quantitative back up information. It was not included with the remainder of the data. The questionable report is referenced by a footnote in Table 2-6. It is interesting to note also that this failure was reported for airborne equipments.

COMPARISON OF K FACTOR

and

OBSERVED SOLDER CONNECTION FAILURE RATE VARIATIONS

TABLE 2-7

Type of Equipment	*Normalized Failure Rate	**K Factor
1. Ground Computers	1.0	1
2. General Ground Equipment	1.4	1
3. Shipboard Equipment	2.1	1
4. Ground Radar	3.5	1
5. Airborne Equipment	8.5	6.5

$$* \frac{\text{failure rate of connection for equipment type}}{\text{failure rate of connection for ground computers}} = \text{normalized failure rate}$$

** See Designer's Reliability Handbook, Hughes Aircraft Company Section 1, page 8

In referring to Table 2-1 to 2-6, it should be noted that some of the reports provided only the number of connection failures and the number of equipment hours of operation. To compute a failure rate, it was necessary to estimate the number of joint-hours of operation. To estimate the number of joint-hours it was necessary to estimate the number of joints or connections within the given piece of equipment. This estimate was performed by multiplying the equipment parts count by a factor of five, this factor was obtained from Hughes Aircraft Company manufacturing experience. The resultant number of joints times the stated equipment operating hours provides a reasonable estimate of joint-hours.

2.3 Discussion of the Results

It seems reasonable to investigate the relation, if any, that exists between standard part failure rates and the connections failure rates presented herein. For example, are connection failure rates high or low when compared to part failure rates? Are the connection failure rates reasonable?

First consider the present state of the art. Table 2-8 presents data on current equipment that has been in the field for a few years. The equipment contains a mixture of analog and digital circuits and represents the results of a reasonable reliable design effort. It employs standard parts, no medium or high-reliability parts, and well designed circuits. Solder connections are used for 90°/o of the connections, while the balance of the connections are crimp connections. It is reasonably maintainable and is used twenty-four hours a day.

The column, Generic Part Failure Rate, was obtained by dividing the total estimated equipment failure rate by the total number of parts considered in the making of the estimate. The correlation between observed and the estimated equipment MTBF is reasonably good.

Now note solder connections from Table 2-3, if the laboratory data and the airborne data are excluded, a range of connection failure rates between .0004%/1000 hours and .00085%/1000 hours is obtained. These failure rates can be compared to the generic part failure rate by considering that an average of five connections are required for each installed part. Multiplying the connection failure rate by five produces what could be called a connections per part failure rate on generic connection failure rate ranging from .002%/1000 hours to .005%/1000 hours.

Thus, worst case connection failure rates are approximately one tenth worst case part failure rates. In the field, therefore, for ten estimated equipment malfunctions, one malfunction should result in a connection repair. This appears to be an extremely high ratio. Regardless of the field reporting technique, any field maintenance personnel required to perform this ratio of connection repairs can be expected to complain about what he would consider a severe lack of quality control. We do not seem to receive this type complaint. More important, for present digital equipment employing higher reliability parts, this ratio can be expected to approach an unreasonable one to one ratio. It would, therefore, appear that for ground equipment the present connection failure rates are considerably higher than expected.

TABLE 2-8 CURRENT GROUND EQUIPMENT RELIABILITY

Parts Count	Generic Part Failure Rate (%/1000 hrs)	Estimated MTBF in Hours	* Observed Field MTBF in Hours
7200	0.052	260	240
9200	0.047	230	230

*These data have been corrected for reporting inefficiency. It was assumed that only 80% of all failures were reported.

However, it also seems reasonable to expect, from the search and analysis performed in this study that the failure rates are too low. It is generally felt that reports tend to present an optimistic reflection of the facts. That is, some failures are not included because they were attributed to other than natural causes. Reports, then, can be considered to present lower bounds on failure rates.

Thus, on the one hand, the connection failure rates are too high, while on the other hand the connection failure rates appear to be low. This seeming paradox can perhaps be explained by either of two arguments:

- The data does not present inherent connection failure rates that can be justified for use in making equipment MTBF estimates or

- Present estimating techniques must be adjusted to include relatively high connection failure rates.

The first argument might be that the bulk of the data presents a quality control defect rate. Except for the data from the Hughes files, it was not possible to separate the data obtained from what could be categorized as quality acceptance report or qualification test reports, from those data obtained from other equipment report. There is reason to believe, then, that the high initial malfunction normally encountered during early test may have biased the data.

The second argument might be that the normal part failure rates used in estimating MTBF already include connection malfunctions as a normal mode of part failure, or that part failure rates are really lower than anticipated, thus allowing a relatively high connections failure rate while not destroying the parity that exists between estimated and field equipment MTBF.

Either argument raises numerous questions concerning the results. This analysis has served to form the basis for a much needed and more thorough investigation.

2.4 Discussion of the Data

The study was conducted solely by gathering and analyzing reliability reports from a wide variety of sources. No controlled test data were generated during the effort. This is pointed out not for the purpose of degrading the results but to make the ground rules and the assumptions of the study clear.

In all, 208 reliability reports were received from both manufacturers and users of electronic equipments from all parts of the United States and from Great Britain.

The reports were gathered from publications and individual companies. They were received in written form and they were recorded from telephone and personal contact conversations. They were received in all degrees of completeness. Some of the reports described every detail of the environmental conditions in effect during the reporting period, some gave general information, and a great many made no mention of operating conditions. Some of the reports described the failure modes in detail, while others recorded only the total number of failures. Some reports defined failure as an open or intermittent circuit, while others included connection resistance as a failure. Some reports differentiated between production methods for the same connection type as in the case of dip

soldering and hand soldering. Most reports did not; therefore, all soldering methods are combined. Some reports described the materials being joined, but most did not. Therefore, reports are combined by general connection type.

The majority of reports covered operating periods during which no failures occurred. Therefore, no point estimate could be made of failure rate for that particular report. Many other reports contained such a small number of observations of failures that conclusive estimates of reliability characteristics were not possible.

The difficulties just discussed were treated in several ways in order to use as much of the data as seemed feasible without introducing undue biases. The spectra of expected environmental operating ranges were divided into intervals that define high, medium and low stresses. On many occasions, broad assumptions had to be made to determine a reports' proper classification. With regard to manufacturing processes and materials, all these data were combined by connection type and by equipment application.

With these explanations as guidelines, the results of this effort are presented as a part of the contribution to the state of the art of reliability. If more accurate reliability estimates are required, they can be obtained from controlled tests.

SUMMARY OF SECTION 3

Section 3 describes the results of the study concerning the effects of environmental stresses on the failure rates of connections. The environmental stress levels thought to be important were chosen and divided into levels of severity. The data were assigned a severity level (high, medium or low). The environmental effects were determined by a multiple linear regression analysis. The data were grouped in three ways for this analysis: by individual reliability reports where failures were reported for each connection type, by the type of equipment or laboratory tests for each connection type, and, by various different combinations of environment for each connection type. The data were analyzed on a computer using a standard regression analysis program. The only environmental stress that showed a measurable effect was mechanical stress on weld connections. The reason that other effects were not measurable is probably related to the accuracy of the environments in the reliability reports received. The relationship between mechanical stress and weld failure may be useful as a tool for accelerated testing.

SECTION 3 - ENVIRONMENTAL EFFECTS ANALYSIS

The second stated objective of this study was the determination of the effects of environmental stresses on the failure rates of electronic circuit connections. In general, it can be said that this objective could not be achieved with the types and amounts of data collected. One effect did display statistical significance. As mechanical stress increased, failure rate also increased for welded connections.

3.1 The Data

Prior to beginning the search for data, the researchers compiled a list of environmental stresses that judgment suggested were the ones most likely to affect connection failure rates. These are listed in Appendix I. Stress severity classifications are also shown. These intervals are designated as low, medium and high. They were constructed based on typical ranges encountered in various military specifications, designers' reliability handbooks, and other technical publications, as well as on engineering judgment.

As a reliability report was found in a publication, or received by mail or personal contact, the researchers attempted to obtain the specific levels of stress under which the equipment was operated. In most instances, this part of the information was incomplete. When the information was incomplete, the decision regarding environmental stress conditions for that particular reliability report was made arbitrarily, based on the fragmentary information in the report. The nature of these decisions can best be illustrated by an example. If a reliability report was received describing operating hours and number of failures on a mobile radar, operating in Tucson, Arizona in June and contained no other information regarding environment, the researchers arbitrarily assigned the following environmental stresses to this piece of data:

Environment	Stress Level	Numerical Rating
Corrosive Agent	low	1
Temperature Cycling	medium	2
Humidity	low	1
Shock	medium	2
Vibration	medium	2
Mechanical Stress	low	1

For purposes of mathematical analysis, low stresses were assigned a numerical value of 1, medium stresses 2, and high stresses 3.

Then with the failure rate as the dependent variable and with the environmental effects as the independent variables, multiple linear regressions were performed on the data. The outcome of these analyses was to identify the environmental effects which contributed to variation in the failure rate of a given connection type.

To exploit every possible way of measuring the effects of environment on failure rate, the data were grouped and analyzed three different ways. Another consideration for the groupings was to attempt to utilize most of the reliability reports. This was done under the assumption that an increased volume of data for analysis would result in a better estimate of the effect being studied.

The ways in which the data were combined for analysis and the reasons for each method are as follows:

a. The individual reliability reports, where failures were reported, were grouped together by connection type. This meant disregarding the reports where no failures occurred. Of course, the disadvantage is that these data represent a valid level of reliability and yet they were unuseable, since it was not possible to calculate a point estimate of the failure rate for use in the regression analysis. Table 3-1 summarizes the number of reports that were used in the analyses where the data were grouped by connection type. Therefore, four regression analyses were performed with the number of observations indicated in Table 5-1 in each (i.e., solder 56, weld 12, wire wrap 4, crimp 4).

Table 3-1. Number of Reliability Reports Collected in Data Search

Connection Type	Reports Collected	Reports Containing One or More Failures
Solder	101	56
Weld	53	12
Wire Wrap	35	4
Crimp	13	4

b. A second way of grouping the data for analysis was by application. In this case, all pieces of data were organized by families related to equipment type or test type. For example, the 101 pieces of failure rate data on solder were classified as follows:

General Ground Equipment	12
Ground Radars	3
Ground Computers	18
Airborne Equipment	17
Shipboard Equipment	4
Laboratory Tests (Modules, Parts)	43
Laboratory Test (Connections)	4
Total	101

The hours and failures for each of these seven classifications were summed to obtain failure rates by application class. These seven failure rates were then considered the dependent variables and were compared with the average environmental effects in a multiple linear regression analysis. Welding was the only other connection type where sufficient data warranted this type of grouping. The groups used were General Ground Equipment, Airborne, Shipboard, and Laboratory Tests. Therefore, this analysis contained only four observations for computational purposes.

This related equipment grouping of the reports enabled the use of all the hours that had been obtained. It combined the reports containing no observed failures with those where failures were observed. The disadvantage was that in combining the reports some of the significant effects may have been obscured. However, the classes used for grouping are ones that judgment suggests are reasonable.

c. The third method of grouping the data for analysis was by selecting the number of environments to be evaluated and then grouping the pieces of data by the different combinations of environment that could occur. To clarify this manner of grouping, consider an example: Suppose we want to evaluate the effects of temperature cycling, humidity and vibration on solder connection failure rate. Assume we have classified the severity of each environment into high, medium, and low. Then there are 27 possible combinations of these three environmental effects at their three levels. For instance, low vibration - low humidity - low temperature represents a different overall effect than low vibration - low humidity - high temperature. Grouping the 101 pieces of solder data into these 27 possible combinations of three environments gave 12 observations based on the quantity and type of data available. The pieces of data which fell into each of the 12 cells were combined to form 12 failure rates for use as dependent variables in the multiple regression analysis as shown in Table 3-2.

Table 3-2 Solder Failure Rates by Environment

			Vibration		
		Temperature	Low(1)	Medium(2)	High(3)
HUMIDITY	LOW	Low (1)	.00032	.00044	.00091
		Med. (2)	.11	.0032	4.17
		High (3)	.00055	No Data	.15
	MED.	Low (1)	No Data	No Data	No Data
		Med. (2)	No Data	.011	No Data
		High (3)	No Data	.0016	No Data
	HIGH	Low (1)	No Data	.0050	No Data
		Med. (2)	.00056	No Data	No Data
		High (3)	No Data	No Data	No Data

The advantage of this form of data combination is that nearly all of the reports that were collected were used in the analysis. The disadvantage appears to be that this method fragments the data to the point that certain of the estimates are based on only a small number of failures and therefore may not be good enough estimates to submit to this type of analysis.

Other than solder, no type of connection had sufficiently varied data to enable an analysis when grouping data in this manner.

3.2 Analyses

Only enough data were available to perform the following seven analyses:

a. Solder vs. temperature, humidity and vibration using 56 point estimates.
b. Weld vs. temperature, vibration and mechanical stress using 12 point estimates.
c. Wire wrap vs. temperature and humidity using 4 point estimates.
d. Crimp vs. temperature and vibration using 5 point estimates.
e. Solder vs. temperature, humidity and vibration using 7 applications.
f. Weld vs. temperature and mechanical stress using 4 applications.
g. Solder vs. vibration, temperature and humidity using 12 environmental combinations.

The raw data for these analyses are listed in Appendix IV.

These data were analyzed on an IBM 7094 computer using a standard program for the solution of multiple linear regression problems.

The output of the program for each of the problems was as follows:

a. Correlation matrix - made up of the correlation coefficients of each independent variable with all other independent variables.
b. Column correlation vectors - the correlation coefficient between the dependent variable and each independent variable.
c. Regression coefficients - the slope of each of the variables.
d. Multiple regression coefficient - the net effect of the independent variables on the dependent variable.
e. F-ratio - the method of testing for the significance of the multiple regression coefficient.
f. t-tests - the method of testing for the significance of the independent variables.

3.3 Results

Of the seven multiple linear regression analyses performed, only one of them showed an environmental treatment with a significant effect on the failure rate of a connection technique. This was the case of weld vs. temperature and mechanical stress. A further analysis indicates that only mechanical stress had a significant effect. The computer output and its interpretation is as follows:

a. Correlation matrix:

	Temperature	Mechanical Stress
Temperature	1.	-.49

The correlation matrix shows the relationship between the independent variables. In this case the coefficient of correlation between temperature and mechanical stress is -.49. This is not significant statistically for the number of observations. Therefore, it must be assumed that the effects of the two variables are not related to one another.

b. Column correlation:

	Temperature	Mechanical Stress
Failure Rate	-.32	.98

From the above, it can be seen that for the data analyzed the coefficient of correlation is .98 between failure rate and mechanical stress. On the other hand, the relationship between failure rate and temperature is -.32, which is not significant. The measure of statistical significance used is the test of the hypothesis that the correlation coefficient equals zero (i. e., no relationship exists between failure rate and mechanical stress). For four observations (i. e., two degrees of freedom), the probability that the correlation coefficient exceeds .95 if no relation exists is only .05. Since it is actually .98 it can be inferred that correlation does exist.

c. The regression coefficients are as follows:

$$b = -.057,\ b_T = .004,\ b_M = .052$$

Therefore, the multiple regression equation is

$$Y = -.057 + .004T + .052M.$$

d. The multiple regression coefficient was .998. This means that nearly all of the variation in failure rate in the data is explained by the net effect of temperature and mechanical stress if the coefficient is found to be statistically significant.

e. The F-test is used to determine if the multiple regression coefficient is statistically significant. The F ratio for this problem is calculated by the formula:

$$F = \left(\frac{n - p - 1}{p}\right)\left(\frac{R^2}{1 - R^2}\right)$$

where

n = number of observations
p = number of independent variables
R^2 = multiple correlation coefficient

For this case the F Ratio is 343.8. From the F tables of the .05 level, for 2 and 1 degrees of freedom, the F ratio must exceed 200 to be significant. Since it does, we may assume that a large portion of the variation in failure rate is due to the net effect of both temperature and mechanical stress.

f. t-tests — In order to determine if the independent variables have an individual effect on failure rate, it is necessary to perform t-tests. This tests the hypothesis that the regression coefficients are equal to 0. If the hypothesis is rejected ($t_T > t_{.05}$), then there is significance. In this case,

$$\left.\begin{array}{l} t_T = 4.89 \\ t_M = 24.85 \end{array}\right\} (t_{.05}, 1 \text{ d.f.}) = 12.706$$

Therefore, mechanical stress has a significant effect and temperature is not different from 0.

A brief summary of the results of each of the multiple regression problems is shown in appendix IV.

3.4 Evaluation of Results

The results of the over-all analysis of the effects of environment on failure rate, are inconclusive. Only one environmental treatment, mechanical stress on welded connections showed a measurable effect. The analysis indicated that failure rate increases as mechanical stress increases. Engineering judgment, however, suggests that vibration, temperature, humidity and other environments also have detrimental effects on the failure rate of various connection types. The reason that these effects were not measurable here, probably is related to the quantity and accuracy of the data which were collected. The data were collected from many different sources throughout the United States and the world. They were from manufacturers and users. They were from different production processes, and different uses were made of the equipment from which data was taken. The reports were from sources who had different failure definitions and different failure reporting systems. These are not shortcomings, however, if all of these differences are known and are enumerated accurately. However, in the majority of cases, the environmental treatments were not explicitly spelled out. Consequently, it was necessary to construct intervals of environmental treatments. Even with this approach, the researchers still had the problem of deciding the magnitude of the severity of the environmental stresses. In most cases, the specification of the category to be used became the arbitrary decision of the researcher instead of having been clearly defined by the reporter or user of the equipment.

The data were thoroughly analyzed by grouping and rearranging them in many different ways. In the final analysis, it must be said that the answers which come out of an analysis can be only as good as the data which go into it. If more accurate measures of the environmental effects are required, they will have to be measured from more accurate equipment or laboratory data.

The one significant effect that was observed (i. e., failure rate of welded connections vs. mechanical stress), bears further investigation. It must be recognized that this result came from a comparatively small number of observations. Therefore, its validity is open to question. While it is recognized that normally mechanical stresses are not applied to connections, the fact that this environmental treatment seems to cause the deterioration of reliability could be a useful relationship. If subsequent study were to substantiate that mechanical stress reduces connection life in some regular pattern, this might represent a tool for accelerating the reliability testing needed to evaluate the reliability of connection types.

SUMMARY OF SECTION 4

The merit index developed here is intended as guide to the designer in the choice of a connection type for a given application. The index presents the most important factors and sub-factors to be considered in choosing a connection type and assigns quantitative values to them. The connection types considered here are solder, weld, crimp and wire wrap. The factors considered are as follows: reliability, design, manufacturing and maintainability. These factors are divided into sub-factors which are then quantified and assigned point ratings. In actual practice, the factors will be given different emphasis, depending on the use of the equipment. These are reflected in the merit index by application weights. The uses considered here are as follows: laboratory versus field, prime versus support and stationary versus mobile applications.

Typical Air Force ground equipments are defined in terms of application classes. The laboratory vs field application measures the accessability vs remoteness of an installation. Similarly prime vs support applications reflects high availability requirements vs non-critical availability requirements, and stationary vs mobile measures the permanence of an installation. Examples demonstrating the use of the Merit Index on four types of equipment are tabulated in Tables 7-1 through 7-4. The discriminatory power of the Merit Index is illustrated when it is shown that wire wrap connections are preferred from the standpoint of reliability, design, manufacturing, and maintainability for use on Laboratory - Prime - Stationary and Laboratory - Support - Stationary equipments. Solder connections are rated highest for Field - Prime - Stationary and Field - Prime - Mobile applications.

SECTION 4 MERIT INDEX

4.1 Definition of the Problem

The merit index developed as a part of this study program is presented as a tool for the use of the designer. It is meant to guide him to the consideration of the most important factors which affect his choice of the type of connection for a given application. The goal of the merit index is to minimize the subjectivity of the designer's decisions by describing the attributes of each factor in quantitative terms.

There were two divergent forces operating on the developers of this tool: the merit index must be simple and it must have good discriminatory power. With regard to simplicity, only the most important factors can be included in the index. With regard to discriminatory power, there are well over 50 sub-factors that can affect the designer's decision to use one connection type over another. However, to list each of these factors and go through the arithmetic of using a merit index this complex would be an uneconomical process. It is recognized that several of the factors weigh more heavily in the decision making process than others. Therefore, the ones that are of minor importance, if considered, would certainly increase the accuracy of the decision, but would increase the complexity of the process. The factors selected for preparing this Merit Index are as follows: Reliability, Design, Manufacturing, and Maintainability. The Merit Index presented here is an attempt to balance ease of use and discriminatory power. Cost has in all cases been excluded from the merit index. This is not to say that it does not affect the designer's final decisions, but simply that it should be considered independently of the factors of interest presented. It is most difficult, of course, to remove cost considerations because they tend to enter even if only in the most subtle manner. Further refinements of the present form of the merit index will likely be required to more completely fulfill this goal.

A fully developed merit index might be applicable to all presently used types of connections. It might also be sensitive to the evaluation of microelectronics and integrated circuitry characteristics. In its actual present state of development, the merit index is most useful for the four types of connection considered in this study; namely, solder, wire wrap, resistance weld, and crimped connections. Further refinements would increase its discriminatory power for these connection types as well as for the new and developing varieties.

The remainder of this section is devoted to a detailed explanation of how the merit index was developed and how it should be used. Paragraph 4.2 describes the formula and the mathematics needed to compare the merits of several connection techniques. Following this is the definition of the factors and sub-factors which are included in the merit index together with a justification for the selection of each. The sub-factors are then quantified and the quantification criteria are explained together with statements which have been developed to describe the degree to which a type of connection possesses a given characteristic. The factors are next weighted to adjust their relative importance in different Air Force ground equipment applications. The final part of the section presents examples illustrating the use of the merit index for several applications of Air Force ground equipment.

4.2 Approach to the Problem

When the designer uses a merit index, he assigns numerical values to factors and sub-factors; adjusts the relative weights of these depending on the end use of the equipment; and sums the adjusted factor weights, over all factors, and sub-factors. This gives a dimensionless index number that represents the desirability of using a given connection technique for a given application.

The above operations can be represented mathematically by the following equation:

$$M = \sum_{i=1}^{n} a_i f_i ,$$

where M = merit index number of a given connection technique for a given application

a = application weight determined by the end use of the equipment

f = factor weight determined by quantifying factors and sub-factors which affect designer's decision when selecting an optimal connection type.

n = number of factors in the merit index

If M_{solder} is greater than M_{weld} for a given application, the user of the merit index would be led to the selection of solder as the connection technique to be used from the standpoint of the factors considered; namely, reliability, design, manufacture, and maintainability.

4.3 Factors and Sub-Factors

The general terminology required to understand the functions and uses of a merit index is defined in the following paragraphs. The following definitions explain the terms used throughout the Merit Index Section of this report:

- Factor — A factor is a broad classification of considerations that the designer uses in evaluating the merit of a given type of connection in relation to its design objectives. In the merit index the factors included are reliability, design, manufacturing and maintainability.

- Sub-Factor — A sub-factor is defined as a specific attribute of a connection technique with which the designer evaluates its merits against its design objectives. Each sub-factor is related to one of the previously mentioned factors. The list of possible sub-factors which could be considered is very large. The sub-factors selected for use in this merit index are those thought to be most influential for giving it adequate discriminatory power without making it overly complex. The sub-factor associated with the factor reliability is joint life. The design sub-factors are connection density and compatibility. The factor manufacturing has the sub-factors preparation, producibility, process control, and inspectability. Maintainability has as sub-factors repair time, repair skills, and repair tools.

Each factor and sub-factor selected for inclusion in the merit index and the basis for its selection is explained in the following paragraphs.

4.3.1 Reliability — Most electronic systems in use today are quite complex. They employ thousands of electronic parts. These parts are formed together into a working package by means of connections. Therefore, the joint life of the type of connection employed has a direct bearing on the reliability characteristics of the equipment or system utilizing it.

In earlier phases of this study program, failure rate information was gathered from all possible sources on four common connection techniques: solder, resistance welding, wire wrap, and crimp. These data were analyzed and used in the construction of the guidelines which constitute the Joint Life sub-factor of this merit index.

4.3.2 Design — The Design factor is an extremely important one for consideration. It has many varied facets. The sub-factors selected for the merit index are mainly those concerned with packaging. The differences in the various connections' performance characteristics, such as current carrying capacity and connection resistance are assumed to be of the magnitude which would not cause a radical difference in the final merit index value. Hence, these are omitted in the interest of ease of use.

The following two sub-factors selected for evaluating the design factor are connection density and compatibility:

- Connection Density — Size is becoming an increasingly important criteria in the design of electronic equipment. This is witnessed by the great volume of work in progress on micro-miniaturization. Therefore the designer is constantly faced with selecting a connection type that will afford him as high a density per unit volume as is feasible as long as other factors do not suffer. It is fitting, therefore, to closely examine the attributes of connection techniques with regard to size or density.

- Compatibility — The present trends of the design of electronics equipments suggests that the type of connection that is the most versatile is more in demand. The principles of modularization require an emphasis in a given direction. Compatibility for use with replaceable modules such as circuit boards is considered a major decision factor because it allows the merit index to give weight to the versatility of techniques that can be universally applied. Other considerations are compatibility with components, and different wire sizes.

4.3.3 Manufacturing — The design considerations with relation to manufacturing are extremely complex. The sub-factors selected of necessity are broad in scope. They are consolidations of logical sub-factors. The manufacturing sub-factors utilized in the merit index are as follows:

- Preparation — This factor recognizes that certain connection types are rendered useful only after a considerable amount of special preparatory operations. As an example, solder requires a specially cleaned and treated surface while wire wrap and crimping require no special preparatory operations other than normal freedom from contamination.

- Producibility – This factor considers the production processes and recognizes the advantages and disadvantages of automation, tooling requirements, and the skill required by the operator who makes the connection. Producibility gives greater worth to a connection technique that can be automated and mass produced because, in general, this results in a more uniform product. Tooling is an item that the designer wants to avoid from certain standpoints. It has the disadvantages of requiring adjustment, calibration, and repair. Hence, the requirement for tooling in the use of a connection type is generally counted a disadvantage. Skill requirements affect producibility because when a process is automated, the operator has less control over factors that affect quality, reliability, scrap, rework, manufacturing time, and scheduling can vary widely. Therefore, the connection techniques which gives the operator the smallest opportunity to alter these characteristics are given preferential treatment.

- Process Control – Each of the various connection types under consideration is subject to numerous process variables. Some of the decisions to be made are as follows: (1) Welding requires the periodic adjustment of pressures and the changing or dressing of the electrodes. (2) Solder requires the correct amount of the correct type of uncontaminated solders and fluxes. This must be coupled with workmanship practices that can vary widely from operator to operator and from the work of the same operator from day to day. (3) Crimping process controls must be applied to the type of crimping tool, its rate of wear, and the operators' crimping technique. (4) Wire wrap process controls must be applied to tool wear, wire size, and wire physical characteristics.

- Inspectability – This factor evaluates the problem of whether or not a connection, once made, can be successfully inspected. The problems considered here are whether or not special inspection tools or techniques are required. It further points to the advisability of sometimes selecting a connection type that has other disadvantages in favor of one that can be inspected reliably.

4.3.4 <u>Maintainability</u> — The ability to repair and maintain a connection in use is a major area of interest when designing for optimum application. The following sub-factors are the most important to be considered in this category:

- Repair Time — The parameter of interest here is the amount of time required to repair a faulty connection when it has failed.

- Skill Required — The consideration of whether or not a repair can be made by the average field technician is important. If a person with special skill is required, the connection type is less desirable.

- Tools and Materials Required — In most operational situations, the quantity and variety of tools required should be minimized. Those types of connections which require complex or special tools are less desirable. Supply problems in the field are always severe and any way in which they can be reduced should be reviewed by the designer.

4.4 Sub-factor Quantification

Simply naming and defining the factors and sub-factors to be considered by the designer in the use of the merit index is not sufficient. Therefore, a quantification technique must be developed for each sub-factor.

The approach used here is to consider the relative merit of each type of connection for each factor and sub-factor. In other words, the four connection types considered in this study are ranked from best to worst for each sub-factor. The quantification process then takes place as follows. If a sub-factor is already in numerical form, then the spectrum of possible values is divided into logical divisions and a point rating is assigned to each of the divisions. If a sub-factor is not in quantitative form, the logical descriptive statements must be developed which accurately describe the characteristics of various levels of merit. Point ratings are then assigned to each of these descriptive statements to create a gradation between the merit of the connection types in question. To equally weigh each factor, the total of the maximum point ratings for each group of sub-factors within a factor must total 100. For example, reliability has only one sub-factor, joint life. The maximum point rating assigned for joint life is 100. Design has two sub-factors. The maximum point rating assigned for each of them is 50 points.

The measurement degrees for each merit index sub-factor are given as follows:

- Joint Life – The point ratings for the merit index were generated by considering the failure rates which were calculated during the data gathering phase of the study. The failure rate estimate for wire wrap was 0.00000037% per 1000 hours. Solder joints were estimated at 0.00057% per 1000 hours. Resistance welds were not statistically different from solder. The intervals were constructed to differentiate between the differences obtained for each connection type. They were selected also in a manner that tried to prevent borderline cases. The numerical point ratings assigned to each interval were based on engineering judgment. The point ratings for joint life are listed as follows:

Category	Point Ratings
Failure rate from: 0 - 0.000001%/1000 hrs	100
0.000001 - 0.001%/1000 hrs	60
0.001 - 0.01%/1000 hrs	30
0.01 - ∞%/1000 hrs	0

- Connection Density – Connection density can be neatly categorized in terms of connections per square inch per 1/4 inch of depth. This criterion presupposes a panel on which point-to-point wiring is carried out, although the definition can easily be extended to include other forms of three dimensional wiring. Welding can be done on a center to center spacing of 0.100 inches. Four leads can be soldered to a post 1/4 inch high. Soldering can be done on 0.200 inch centers with 2 leads attached to a 1/4 inch high post. Crimping is capable of the same density as solder. Wire wrap can be used on 0.200 inch centers with one lead per 1/4 inch post. The point ratings assigned reflect the fact that connection types are seldom utilized to their maximum density. They are listed as follows:

Category	Point Ratings
Over 100 connections/square inch	50
30-99 connections/square inch	30
10-29 connections/square inch	10
less than 10 connections/square inch	0

- Compatibility — Compatibility is rated based on four situations. These are connection compatibility with circuit boards, components, point to point wiring, and different wire sizes and types. Solder joints are useful without restriction in all four cases; hence, they are given the highest rating. Welding is compatible with point-to-point wiring and with components. Weldable laminar wiring harnesses do exist, but they are relatively undeveloped and are presumed to be less desirable than solderable etched circuit boards. At present, welding of stranded wire is not a practical method. Since this eliminates half of the possible wire types that might be used, a lower total point rating is assigned to welding than to solder. Crimping is useful for point-to-point wiring and different wire sizes. Although there is a group of switches that normally use screw lugs with crimped on terminals, they are such a special case that little weight is assigned to this connection technique with regard to compatibility with components. Wire wrap connections are the least compatible type, since the whole system has been developed around a particular geometric concept. While it is true that special tools have been developed for a number of wire wrap sizes, the switching of tools is not compatible with the basic concept of wire wrap assembly. Wire wrap connections, therefore, are described in terms of the fourth statement in the following listing:

Category	Point Ratings
Compatible with circuit boards, components, all wire sizes and types, and point-to-point wiring	50
Compatible with components, and point-to-point wiring; partially compatible with circuit boards and different wire sizes and types	25
Compatible with point-to-point wiring and different wire sizes and types, incompatible with components and circuit boards	20
Compatible with point-to-point wiring, incompatible with circuit boards, components and different wire sizes and types	10

- Preparation — This sub-factor encompasses all forms of lead dressing and preparation including cleaning, cutting, sizing and shaping. Welding requires no special lead preparation if the lead materials are of a weldable nature. Several laboratory tests have been performed which indicate that special chemical and mechanical cleaning processes have no effect on the

quality of welded circuits if materials and components have been given normal storage and handling. Soldering, on the other hand, requires a significant amount of lead preparation. This is not always recognized, since it is normal for the components to be manufactured with leads pre-plated. Neither wire wrap nor crimping require any special treatments before use. The assignment of point ratings is based on engineering judgment and experience. The assignments are as follows:

Category	Point Ratings
Requires no special preparation before making connection	25
Requires special cleaning and preparation before making connection	15

- Producibility — With very little adjustment, the producibility sub-factor could be fragmented into several other parts. However, the present definition is an attempt to create a broad category that still has sufficient sensitivity.

Two kinds of automatized production are to be considered. The first is bulk processing which is typified by the various forms of dip and flow soldering devices. When the production efficiency is based on these processes, soldering is rated high. The second is the equipment for mechanized random wiring. The most efficient of these is the wire wrap process. A number of machines are in use today which can make this type of connection. Crimped connections are rated slightly below wire wrap even though an experimental machine has been constructed and seems satisfactory. Although to date there is no equipment for welding which is comparable to that available for the other connection types, the potentialities for mechanizing are so great that welding was not completely ignored in the assignment of point ratings. With regard to tooling, welding requires the greatest amount.

The consideration of skill requirements is concerned with the relative ease of making a good joint. Stated another way, it is concerned with how much control the operator has over the things that could go wrong. Soldering rates low in this respect because of the problems of flux control and removal, the possibility of cold joints and rosin joints, and because of the problem of voids and entrapments. Wire wrap is rated high because the available hand tools reduce the chance of a poorly made joint. The only error possible with a power wire-wrap tool is bending the post and unless this is excessive, it will cause no harm. Crimped joints are almost as easily made as wire-wrap joints. The fact that they are frequently used in conjunction with tapered pins increases the problems, since these can be easily damaged. There is also the possibility of over or under-crimping. In the consideration of skill requirements, welding rates just above soldering. Although the machine can produce consistently good connections, skill is required to correctly align and adjust the process variables. The point assignments are as follows:

Category	Point Ratings
Can be automated, requires special tooling, and low skill level	25
Can be automated, required special tooling and equipment, moderate skill level	20
Can be partially automated, requires special tooling, requires moderate skill level	15
Cannot be automated, requires special tooling, moderate skill	10
Cannot be automated, requires no tooling, high skill	10

- Process Controls – Process control includes all variables that must be monitored during the manufacturing operation in order to maintain the quality of the connection. Due to the diversity of the processes being compared, a simple quantification is most difficult. For example, in the soldering process, variables requiring control are solder bath temperature, contamination level, time of exposure, flux activity and application, and flux removal. These vary depending on the details of the specific process.

Wire wrap process control consists of monitoring bit wear, wire size, temper, and finish, as well as the control of terminal size, temper, and finish.

With crimped connections, the wear of the crimping tool, the force and motion of the crimper and wire stripper, and the dimensions, temper, and finish of the crimp on lug and the wire must be monitored.

In the welding process, the wire, post size, and alloy must be controlled. Further factors of interest are the energy-force schedule, the placement of the weld, stripping of the wire, and the condition of the weld electrodes.

Many of the items, that are considered, are controlled through purchase specifications, but the possibility remains that they will vary enough to cause difficulty. Therefore, the highest point ratings developed above are assigned to the connection techniques requiring the fewest number of process controls. The assignments of point ratings are as follows:

Category	Point Ratings
Infrequent tool or machine adjustments required, moderate rate of tool wear, no additional materials required	25
Infrequent tool or machine adjustments required, slow rate of tool wear, no additional materials required	20
Frequent tool or machine adjustments required, high rate of tool wear, no additional materials required	15
No machine or tool adjustments required, no tool wear, additional materials needing strict materials controls required	10

Category	Point Ratings
Infrequent tool or machine adjustments required, low rate of tool wear, additional materials needing strict materials controls required	5

- Inspectability — This is a difficult factor to grade. If the assembly is properly designed and the processes properly established, inspection for joint quality is required only for soldering and welding. In the other cases, the yield is so high that the likelihood of an inspector finding a poor joint, even if it is there, is small. In the latter instance, inspectability degenerates to a determination of whether or not the joint was made, and whether or not the process is performing properly. In a mechanized operation, only the latter becomes important.

By restricting the considerations to manual operations, it is possible to establish the following relationships:

a. Wire-wrap and crimping get the top rating because they do not require detailed inspection

b. Welding gets a lower rating because it is necessary to inspect for weld placement and because inspection to see that a weld has actually been made is more difficult, due to the relatively small size of the weld.

c. Soldering gets a very low rating because there are so many possible defects that can be produced and because many of the defects are concealed.

The point rating assignments are as follows:

Category	Point Ratings
Easy to recognize defective connection	25
Moderately easy to recognize defective connection	15
Very difficult to recognize defective connection	5

- Repair Time Required — The extension of manufacturing fabrication times to field repair based on user environments was used to quantify the repair time required. The data assume that the person making the joint is of average skill and has the proper tools at hand. The average time estimate for a crimp or wire wrap repair is 45-55 seconds. For solder, it is 15-30 seconds and welding is 1-3 minutes. Although it is recognized that welds cannot be repaired by welding, the assumption here is that the welded connection can be soldered. The solder repair of a weld requires extra time for cleaning and fluxing. However, it is not disqualified when considering maintenance. The point ratings assigned to each of the repair time intervals were based on engineering judgment. They are listed as follows:

Category	Point Ratings
Repair requires from 0 - 30 seconds	33.3
Repair requires from > 30 - 60 seconds	20
Repair requires from > 1 - 3 minutes	10
Repair requires > 3 minutes	0

- Repair Skill Required – When considering all possible situations, the skill required for repairing connections varies considerably. The categories and their corresponding point ratings are designed ro reflect the skill required. Since soldering requires a skilled person and it has been assumed that welded connections can be repaired by soldering, solder and welded connections are assumed to require the same skill for repair. Wire wrap and crimping connections require a semi-skilled person to perform repairs. The categories and their respective point ratings are as follows:

Category	Point Ratings
Unskilled person required	33.3
Semi-skilled person required	20
Skilled person required	10
Specialist required	1

- Maintenance Tools Required – The complexity of the tools required to repair a connection in the field varies considerably. Solder joints require only the most common tools. Crimping and wire wrap require special tools. Welds which have failed are assumed to be repaired by soldering. The point assignments are as follows:

Category	Point Ratings
None required	33.3
Standard types required	20
Special types required	10

4.5 Application Weights

In paragraph 4.4, the most important factors and sub-factors that should be included in the merit index were selected and defined. Each sub-factor was described in several degrees of importance and point ratings were assigned to each level. Consequently, any connection that a designer wants to evaluate should be categorized according to the statements and point ratings which were developed.

The factors and sub-factors which have been discussed are tabulated below by connection type:

	Solder Point Rating	Weld Point Rating	Wire Wrap Point Rating	Crimp Point Rating
Reliability				
Joint Life	60	60	100	30
Design				
Density	30	50	10	30
Compatibility	50	25	10	20
Manufacturing				
Preparation	15	25	25	25
Producibility	25	10	20	15
Process Control	10	15	25	20
Inspectability	5	15	25	25
Maintenance				
Repair Time	33.3	10	20	20
Repair Skill	10	10	20	20
Repair Tools	20	20	10	10

In actual practice, the factors are given different amounts of emphasis, depending on the use of the equipment. Application weights are devised in the following paragraphs which will adjust the relative weights assigned to each factor and thereby convert the merit index into a usable tool. The types of applications considered are based on the end uses of various families of Air Force ground equipments. The three application differences described below suffice to establish the category of end use.

The initial differentiation is between laboratory and field equipments. Laboratory equipments are defined as those used in as ideal an environment as is possible. They are installed for use at a permanent base or installation. They perform their functions under mild environmental stress conditions. Since they operate at an accessible installation, equipments of this type receive expert maintenance and have the benefit of more sophisticated installation and operational procedures. On the other hand, a field installation is one in which the installation is looked upon as remote. Therefore, the designer would be more concerned with a differing set of criteria which would reflect the variations in severity of those two applications.

A second phase of application differences is that of prime versus support use. If a piece of ground equipment is for prime use, it must be ready to perform its duties immediately, quickly and successfully. If it is performing a support function it does not require such strict considerations with regard to availability for use. Hence, the end use of the equipment would guide the designer in the relative weights which he applied to the design factors.

A third set of comparative application considerations is whether the equipment will be stationary or mobile. Mobile equipments are defined as those which are moved frequently from one location to another. Stationary equipments are installed permanently. The design features in mobile equipments will have to be stressed because of consideration for small size and light weight.

The following table shows the application weights that have been developed for various classes of Air Force ground equipment:

	Lab, Prime, Stationary	Lab, Support, Stationary	Field Prime, Stationary	Field Prime, Mobile
Reliability	10	10	10	15
Design	25	20	30	50
Manufacturing	50	65	40	25
Maintainability	15	5	20	10
Total	100	100	100	100
Typical Equipment Examples	SAC Hq. Commanded Computer	BASE Payroll Computer	BMEWS Radar	Mauler, MMRBM

In the overall evaluation, the design and manufacturing factors will make up between 70 and 85% of the application points. This is understandable because of the importance of those two factors. At the other end of the spectrum, reliability and maintainability are assigned between 15 and 30% of the total application weighting.

To follow through the reasoning used in determining the application weights consider, as an example, a piece of field - prime - mobile equipment. In prime equipment the mission requires a high probability of success for any given mission, therefore high availability is essential. But since this equipment is to be mobile, weight considerations limit the amount of maintenance equipments and the replacement part inventory. The remoteness of field equipment also presents a logistics problem with respect to obtaining replacement parts and the services of specialized maintenance personnel. For these reasons high availability is achieved by emphasizing high reliability. Maintainability is also considered but it is subordinate to reliability. Reliability is assigned an application weight of 15 and maintainability 10. The requirement for mobile equipments to be light weight makes design factors such as packaging density important. Mobile equipments are also subjected to more severe environmental conditions such as vibration and shock when being moved. Therefore the design factor is stressed to allow the equipment to be compact and rugged. Design is assigned an application weight of 50 for field - prime - mobile equipments. Because of the importance of the other factors manufacturing is weighted less. It is assigned an application weight of 25.

4.6 Examples of Merit Index Use

The usefulness of the merit index may be evaluated by considering several examples. For this purpose, the four connection types studied in this program are evaluated for application in four classes of Air Force ground equipment.

4.6.1 Laboratory-Prime-Stationary Applications — An example of a laboratory-prime-stationary equipment is a command computer for use in an installation such as SAC Headquarters. This is a permanent installation where sufficient repair facilities and space are available. Immediate repairs are not necessary because an adequate amount of redundancy exists in the circuitry and in equipment quantities. Consequently, maintainability is given an application weight of 15. Reliability is weighted at 10 because the environments experienced are not severe and because the redundancy exists in the equipments. The design factor is rated at 25 because the equipment is probably fairly complex and because the redundant circuitry suggests that packaging problems are important. On the other hand, the laboratory type installation does not make the problem acute, since an installation of this importance would have ample space and the equipment need not be miniaturized. The manufacturing factor is assigned the application weight of 50 for laboratory-prime-stationary equipment use. Since the equipment is complex, many thousands of connections are used. Therefore, a connection technique that minimizes the manufacturing problems should be selected.

Each of the four connection techniques are given point ratings from the ten subfactor tables. For example, the failure rate of a wire wrap connection is given as 0.00000037%/1000 hours based on the reliability reports shown during the study. Comparing this estimate to the subfactors, it can be seen that wire wrap fits into the failure rate interval of 0 - 0.000001%/1000 hours which is evaluated at 100 points. The joint life of 100 is multiplied by the reliability application weight which for a laboratory-prime-stationary type of equipment is 10. The product of these two is 1000. In a like manner, each subfactor is given the appropriate number of points for its merit attributes and

multiplied by its respective application factor weight. The operation is continued for as many connection types as the designer cares to compare. The summations of the products of the sub-factors and factors point ratings results in a grand total merit index number for each connection technique. The details of these calculations are shown in Table 4-1. The merit index number for wire wrap connections is 7000 points out of a possible 10,000. Therefore, when compared to 6550 points for crimp, 6325 for resistance welding, and 6300 for soldering, the wire wrap type of connection is adjudged the most desirable for the application under consideration.

4.6.2 Laboratory-Support-Stationary Applications — An example of a Laboratory-support-stationary equipment is a computer that performs accounting operations such as payroll and other administrative calculations. For this application, the environment is mild and reliability is rated at 10. Maintainability is not critical, since a failure of the equipment is not critical in the sense of tactical considerations. Therefore, it is assigned a 5 application weight. An equipment of this type is standard in nature and design considerations are minimized. The heavy emphasis is placed on the manufacturing factor which is assigned at 65. Usually, an equipment of this type is produced in relatively large quantities. Therefore, the importance of connection types that display good manufacturing features is stressed by this weighting procedure.

Table 4-2 gives the detailed merit index calculations for the four connection techniques considered in this study. Wire wrap at 7825 has the highest merit index number for this application. It is followed by crimp at 7075, welding at 6525, and solder at 6092. Wire wrap is concluded to be the connection technique with the most merit for use in laboratory-support-staionary applications.

4.6.3 Field-Prime-Stationary Applications — A typical equipment that could be classified as field-prime-stationary is a BMEWS radar. Due to the tactical nature of this installation, minimum downtime is considered of prime importance and maintainability is given an application weight of 20. If a failure occurs, the repair must be made as quickly as possible. In the field, the variety of repair skills and tools needed must be minimized. During tactical operations, a connection must have the advantage of both quick and easy repair. Reliability considerations are important because of the tactical aspect of the functions being performed and because of the rugged environmental stresses encountered. Design factors are rated at 30, since field equipment must be compact and adaptable to any of several methods of operational configurations. Manufacturing factors are rated at 40, since tactical problems dictate the selection of a connection technique that can be produced efficiently in great quantities with a minimum amount of process controls.

Table 4-3 summarizes the calculations used in arriving at a Merit Index number for Solder, Resistance Weld, Wire Wrap and Crimp. For the particular application solder is rated at 6466, Wire Wrap 6400, Crimp 6200 and Weld 6250. The range of merit for an application such as a BMEWS radar is very narrow. A closer analysis of the sub-factor totals points out how the application weights give emphasis where it is logically required. For example, solder is the most maintainable technique and this is desirable for a field installation. The Merit Index rated solder highest for this factor with 1266 points. For manufacturing, wire wrap weighed most heavily because it results in less difficulty in the production of a complex equipment. Wire wrap is rated lowest for the design factor due to its poor compatibility and packaging characteristics.

TABLE 4-1

LABORATORY - PRIME - STATIONARY EQUIPMENT MERIT INDEX CALCULATIONS

(SAC Hq-Command Computer)

		SOLDER		WELD		WIRE WRAP		CRIMP	
	Application Weight	Point Rating	Pt. x Rate Appl. Wt.	Point Rating	Pt. x Rate Appl. Wt.	Point Rating	Pt. x Rate Appl. Wt.	Point Rating	Pt. x Rate Appl. Wt.
Reliability									
Joint Life	10	60	600	60	600	100	1000	30	300
Sub Totals			600				1000		300
Design									
Density	25	30	750	50	1250	10	250	30	750
Compatability	25	50	1250	25	625	10	250	30	500
Sub Totals			2000		1875		500		1250
Manufacturing									
Preparation	50	15	750	25	1250	25	1250	25	1250
Producibility	50	25	1250	10	500	20	1000	15	750
Process Control	50	10	500	15	750	25	1250	20	1000
Inspectability	50	5	250	15	750	25	1250	25	1250
Sub-Totals			2750		3250		4750		4250
Maintainability									
Repair Time	15	33.3	500	10	150	20	300	20	300
Repair Skill	15	10	150	10	150	20	300	20	300
Repair Tools	15	20	300	20	300	10	150	10	150
Sub-Totals			950		600		750		750
MERIT INDEX NUMBER			6300		6325		7000		6550

TABLE 4-2

LABORATORY - SUPPORT - STATIONARY EQUIPMENT MERIT INDEX CALCULATIONS

(Base Payroll Computer)

		SOLDER		WELD		WIRE WRAP		CRIMP	
	Application Weight	Point Rating	Pt. x Rate Appl. Wt.	Point Rating	Pt. x Rate Appl. Wt.	Point Rating	Pt. x Rate Appl. Wt.	Point Rating	Pt. x Rate Appl. Wt.
Reliability									
Joint Life	10	60	600	60	600	100	1000	30	300
Sub-Totals			600		600		1000		300
Design									
Density	20	30	600	50	1000	10	200	30	600
Compatibility	20	50	1000	25	500	10	200	20	400
Sub-Totals			1600		1500		400		1000
Manufacturing									
Preparation	65	15	975	25	1625	25	1625	25	1625
Producibility	65	25	1625	10	650	20	1300	15	975
Process Control	65	10	650	15	975	25	1625	20	1300
Inspectability	65	5	325	15	975	25	1625	25	1625
Sub Totals			3575		4225		6175		5525
Maintainability									
Repair Time	5	33.3	167	10	50	20	100	20	100
Repair Skill	5	10	50	10	50	20	100	20	100
Repair Tools	5	20	100	20	100	10	50	10	50
Sub-Totals			317		200		250		250
MERIT INDEX NUMBER			6092		6525		7825		7075

TABLE 4-3

FIELD - PRIME - STATIONARY EQUIPMENT MERIT INDEX CALCULATIONS

(BMEWS RADAR)

		SOLDER		WELD		WIRE WRAP		CRIMP	
	Application Weight	Point Rating	Pt. x Rate Appl. Wt.	Point Rating	Pt. x Rate Appl. Wt.	Point Rating	Pt. x Rate Appl. Wt.	Point Rating	Pt. x Rate Appl. Wt.
Reliability									
Joint Life	10	60	600	60	600	100	1000	30	300
Sub-Totals			600		600		1000		300
Design									
Density	30	30	900	50	1500	10	300	30	900
Compatibility	30	50	1500	25	750	10	300	20	600
			2400		2250		600		1500
Manufacturing									
Preparation	40	15	600	25	1000	25	1000	25	1000
Producibility	40	25	1000	10	400	20	800	15	600
Process Control	40	10	400	15	600	25	1000	20	800
Inspectability	40	5	200	15	600	25	1000	25	1000
Sub-Totals			2200		2600		3800		3400
Maintainability									
Repair Time	20	33.3	666	10	200	20	400	20	400
Repair Skill	20	10	200	10	200	20	400	20	400
Repair Tools	20	20	400	20	400	10	200	10	200
Sub-Totals			1266		800		1000		1000
MERIT INDEX NUMBER			6466		6250		6400		6200

4.6.4 Field-Prime-Mobile Applications — An equipment for the field-prime mobile application is a mobile Air Defense System. Equipments in such a system must operate in the most severe environments. They must be compact because of space and weight limitations. The design factors are rated high at 50 because an equipment employed for these purposes must withstand shock, vibration, inclement weather, extreme temperatures and still be ready when it is needed.

Table 4-4 shows the details of the Merit Index calculations for a field-tactical-mobile equipment. If a designer selects the most desirable connection technique from the standpoint of reliability, design, manufacturing, and maintainability using this table, he will choose solder with its rating of 6908. Welding is rated at 6675, crimp at 5575 and wire wrap at 5375.

4.7 Discrimination

To illustrate the details of the discriminatory power of the Merit Index, the sub-factor compatibility must be considered. From paragraph 4.4, solder is most compatible with circuit boards, components, all wire sizes and point-to-point wiring. Connections techniques having these attributes are assigned a point rating of 50. On the other hand, wire wrap is most compatible for point-to-point wiring, but incompatible with circuit boards, components, and different wire sizes and types. Therefore, it is rated at 10 points. When the two connection techniques are multiplied by the application factor of 50, solder is rated at 2500 points, while wire wrap is only 500 points. These arithmetic procedures are carried out for all factors and sub-factors. After points are assigned for each factor and sub-factor and multiplications performed, the resulting products are summed for each connection type. The result of the summation is the Merit Index number for the connection technique.

The final judgment with regard to the discriminatory power of the Merit Index lies with the comparison of the Merit Index numbers. In the field-prime-mobile application solder joints are preferred over wire wrap by well over 15%. This preference is based on considerations for reliability, design, manufacturing, and maintainability factors. Judgment and experience suggest that this magnitude of difference is reasonable. The addition of other factors to the Merit Index might result in a more accurate set of numbers, but the accuracy would come at the sacrifice of simplicity and ease of use. A further refinement of some of the quantifications and application factors would result in greater accuracy.

4.8 Validation

The Merit Index as presented in this report is an initial attempt at the solution of an extremely complex set of problems. Its objective is to quantify the worth of factors that up until now have been considered subjectively. How well the researchers have succeeded in attaining their stated objectives will be measured in terms of the utility of this tool to the people charged with making decisions for selection of connections.

TABLE 4-4

FIELD - PRIME - MOBILE EQUIPMENT MERIT INDEX CALCULATIONS

(Mauler, MMRBB)

	Application Weight	SOLDER Point Rating	SOLDER Pt. x Rate Appl. Wt.	WELD Point Rating	WELD Pt. x Rate Appl. Wt.	WIRE WRAP Point Rating	WIRE WRAP Pt. x Rate Appl. Wt.	CRIMP Point Rating	CRIMP Pt. x Rate Appl. Wt.
Reliability									
Joint Life	15	60	900	60	900	100	1500	30	450
Sub-Totals			900		900		1500		450
Design									
Density	50	30	1500	50	2500	10	500	30	1500
Compatibility	50	50	2500	25	1250	10	500	30	1000
Sub-Totals			4000		3750		1000		2500
Manufacturing									
Preparation	25	15	375	25	625	25	625	25	625
Producibility	25	25	625	10	250	20	500	15	375
Process Control	25	10	250	15	375	25	625	20	500
Inspectability	25	5	125	15	375	25	625	25	625
Sub-Totals			1375		1625		2375		2125
Maintainability									
Repair Time	10	33.3	333	10	100	20	200	20	200
Repair Skill	10	10	100	10	100	20	200	20	200
Repair Tools	10	20	200	20	200	10	100	10	100
Sub-Totals			633		400		500		500
MERIT INDEX NUMBER			6908		6675		5375		5575

It is suggested that the best method for validating the Merit Index is to submit it for consideration to all persons who have a knowledge and interest in the subject of connection techniques. Doubtless many improvements and refinements can be added to the work begun here.

SUMMARY OF SECTION 5

The degree of attainment of each of the three program objectives is discussed. Failure rates calculated from the reliability reports gathered during the data search are presented for four connection types; namely, solder, resistance welding, wire wrap and crimp. Also, failure rates, based on equipment classes and applications, are presented. These are shown in Table 2-1. The results of a mathematical analysis which evaluates the effects of various environments on connection failure rates is summarized. The results were inconclusive due, probably, to the quantity and accuracy of the data available. A Merit Index for the use of the designer is proposed to enable him to evaluate the desirability of various connection techniques for Air Force ground equipments from the standpoint of reliability, design, manufacturing, and maintainability factors. The use of the Merit Index is demonstrated in Table 2-2. Merit Index numbers are summarized for solder, resistance welding, wire wrap, and crimp connections as applied to several different equipments and applications.

SECTION 5 — CONCLUSIONS

This section summarizes the conclusions of the study in terms of each of the three stated objectives.

5.1 Failure Rate Estimates

5.1.1 Failure Rates by Type of Connection — Sufficient data were available to compute failure rates for the four types of connections given in Table 5-1. The connection failure rates are totaled separately, by connection type, according to whether the data was contained in equipment reports or laboratory reports.

Significance tests at the 0.10 level were run on the connection failure rates listed by connection type. The results of these tests show that no statistically significant differences exist between the resistance-welded connection failure rate and the solder connection failure rate, nor between the resistance-welded connection failure rate and the crimp connection failure rate.

5.1.2 Failure Rates by Application — The data obtained was divided into the eight classes which are shown with their associated failure rates in Table 5-1. Classes 1 to 5 represent data obtained from the operation of the general types of electronic equipment shown. They are presented in order of their failure rates from lowest to highest. Ground computers have the lowest failure rate and airborne equipments have the highest failure rate. This order is consistent with the failure rate environmental modification factors contained in most reliability handbooks. Classes 6 to 8 are data obtained from special laboratory test results and cannot be compared with actual use conditions.

Failure rates calculated from laboratory tests are much higher than those computed from actual equipment operation. This is understandable, since most laboratory test seek to reduce test time by inducing failures through the specification of severe environmental stresses or by worst case testing. Additionally, some hybrid and experimental connections were also tested in the laboratory. The data on vacuum tubes are based upon laboratory life tests.

It is interesting to note that both the lowest and highest failure rate was obtained for the same connection type: wire wrap. The highest failure rate, 0.45%/1000 hours resulted from laboratory tests to determine process limitations. The lowest, 0.00000037%/1000 hours resulted from data on a ground computer exhibiting only one failure in over 270 billion connection operating hours.

5.1.3 Discussion — The objectives of the failure rate estimates have been achieved to the extent that data has been collected and analyzed for six types of connections. From Table 5-1 it is also clear that many gaps in the data still exist.

Perhaps most important in the results is the value of the connection failure rates themselves. The failure rates appear too high according to present reliability-estimating data and too low according to analysis of data published in reports on equipment operation. A solution to this paradox could involve an investigation into the fundamentals of current reliability-estimating techniques

TABLE 5-1 FAILURE RATES BY TYPE OF DATA

Type of Data	Solder	Resistance Welding	Wire Wrap	Crimp
1. Reports on Ground Computers	0.00040	no data	0.00000037	0.0016
2. Reports on General Ground Equipments	0.00057	0.00019	no data	no data
3. Reports on Shipboard Equipments	0.00085	no data	no data	no data
4. Reports on Ground Radars	0.0014	no data	no data	no data
5. Reports on Airborne Equipments	0.0034	0.0079	*no failures	**
EQUIPMENT TOTAL	0.00057	0.00070	0.00000037	0.0016
6. Laboratory tests on Vacuum tubes	No data	0.0018	No data	No data
7. Laboratory tests on Connections	0.010	No data	0.45	no failures
8. Laboratory tests on Modules, Cards and Parts	0.027	0.038	no data	no data
LABORATORY TEST TOTAL	0.027	0.0070	0.45	no point estimate

*The Airborne report data on wire wrap is combined with computers report data on wire wrap to obtain the equipment total failure rate for wire wrap.

**0.00087%/1000 hour quoted with no quantitative back-up data. Additional information contained in Appendix.

by parts consideration. The analysis and the resulting paradox form the basis for a much needed and more thorough investigagion. Failure rates are discussed in more detail in paragraph 2. 5.

5. 2 Conclusions from the Analysis of Environmental Effects

The reliability reports gathered during the study were analyzed in an attempt to find the relationships that exist between connection failure rates and the various environments under which they operate. In general, it was not possible to measure environmental effects using these types and quantities of reliability reports because the reports were very incomplete regarding the exact environmental conditions under which the equipments operated. Despite the shortcomings of the data, environmental stress intervals were developed and all the reports were arbitrarily placed into the categories that suited them best. Mathematical analyses in the form of multiple linear regressions were performed on several different groupings of data in an attempt to measure the effects of temperature cycling, corrosive agents, humidity, shock, vibration, and mechanical stress. Only minor success was obtained in the search for significant environmental stresses. The overall conclusion is that the data gathered were either not accurate enough to measure environmental effects on the failure rate of connections, or the variations noted were due to factors not considered. Judgment and experience suggest the former conclusion. A secondary conclusion was that sufficient quantities of data generated under all possible combinations of environment and equipment application were not found. However, in the light of the results of the analyses performed, where data was sufficient, it can be assumed that a greater quantity of data would not have materially altered the outcome of the study.

The one factor which displayed a statistically significant effect in the multiple linear regression analyses was mechanical stress on resistance-welded connections. As mechanical stress increased failure rate increased. This conclusion, however was based on a small quantity of information and further verification is probably in order.

5. 3 Merit Index

The merit index which has been developed is a tool for the designer's use in selecting the most desirable connection type from the standpoint of reliability, design, manufacturing, and maintainability factors. Each of the above four factors are divided into sub-factors which are defined in terms that describe a connection's characteristics. The sub-factors are quantified by assigning numerical values to the levels of merit defined for each connection. The reliability factor contains only one sub-factor: joint life. The design factor is sub-divided into connection density and compatibility sub-factors. The manufacturing factor contains preparation, producibility, process control and inspectability sub-factors. The maintainability factor is made up of repair time, repair skills, and repair tools sub-factors.

The end use of an equipment dictates the emphasis which a designer will give to the factors selected for use in the Merit Index. Therefore, Application factors have been developed which vary the relative weights assigned to each factor based on laboratory versus field use, support versus prime use, and stationary versus mobile use.

The factors and sub-factors included in the merit index are not an exhaustive list. They represent the researcher's opinions of those which exert the greatest effect on the desirability of using a given connection. It is felt that the factors selected give the greatest amount of discriminatory power without making the tool unwieldy by the inclusion of an excessive number of factors. The added accuracy gained by the inclusion of more factors and sub-factors would likely not offset the increased complexity introduced into the use of the merit index.

The application of the Merit Index to the major classes of Air Force ground equipment results in the following table of Merit Index numbers by connection type.

Table 5-2. Merit Index Numbers by Application and by Connection Type

Connection Type	Applications			
	Laboratory Prime Stationary	Laboratory Support Stationary	Field Prime Stationary	Field Prime Mobile
Solder	6299.5	6091.5	(6466)	(6908)
Resistance Weld	6325	6525	6250	6675
Wire Wrap	(7000)	(7825)	6400	5375
Crimp	6550	7075	6200	5575
Typical Application Equipments	SAC Hdqrs. Command Computer	Base Payroll Computer	BMEWS Radar	Mauler, MMRBM

The Merit Indexes in Table 5-2 indicate that solder joints are preferable for Field-Prime-Mobile equipments and for Field-Prime-Stationary equipments, and that wire-wrap connections are preferable for Laboratory-Prime-Stationary and Laboratory-Support-Stationary applications. It must be stressed, however, that these index numbers refer to the designer's evaluation based on the reliability, design, manufacturing, and maintainability factors only.

The Merit Index, as developed during this study, is constructed for the evaluation of all connection types. However, the details of its construction were based mainly on the characteristics of solder, resistance welding, wire-wrap, and crimped connections. It is expected that further refinements can increase the scope and discriminatory power of this tool without seriously impairing its use through increased complexity.

SUMMARY OF SECTION 6

The study has produced interesting results and raised questions which remain unanswered. Further data on connection failure rates should be gathered from sources who maintain good reliability records. Additional effort should be applied to obtaining failure rate data on ultrasonic weld, thermal compression bond, gallium alloy and gold-foil connection types. Controlled tests should be conducted to measure the effects of environmental stresses on connection failure rates. Additional effort should be applied to the refinement of the Merit Index. The Merit Index should be validated by actual use by a select group of personnel working in the field of electronic packaging.

SECTION 6 – RECOMMENDATIONS

Each phase of the study produced several interesting results. Likewise, the investigations raised questions which still remain unanswered. This section of the report presents recommendations which should result in a significant refinement of the findings of the study.

6.1 Data with Greater Accuracy

As a result of the study just completed, it is apparent that good reliability records on connections can be found. Also, it was apparent that there were reasons to question the magnitude of the failure rates calculated from such a wide variety of data sources. To improve the estimates of failure rates on the four types of connections investigated, more data is required from sources with good record keeping systems. The data gathered from sources which have better record keeping systems should cover a spectrum of ground equipments and applications. For example, failure rate data by connection types from the equipment classes listed below might serve to measure typical differences of interest:

Equipment Class	Connection Type	Connection Quantity	Operating Hours	No. of Failures	Types of Failures
Laboratory Radar					
Stationary Field Radar					
Mobile Field Radar					

A complete record of environmental operating conditions should accompany each such report. With the correct sources selected, information could be collected concerning manufacturing processes, and quality assurance results. Completed failure analyses should be performed as a result of each equipment failure to ascertain whether the malfunction was due to a part or to a connection. If the records were sufficiently accurate, failure times could be recorded and hence failure distributions could be estimated. Similar data should be gathered in a planned manner from several sources covering several equipment types and applications.

6.2 Data on Additional Connection Types

In the early stages of the search, progress was very slow. However, as experience was gained, greater quantities and varieties of information were found. Consequently, greater skill was used in the latter stages of the study. This skill helped to determine what information to gather and which were more productive sources.

In the final stages of the study, data were still being received. Several reports are even now enroute. Therefore, it is apparent that valuable reliability information on the connection types of interest is available and can be found and analyzed.

In addition to solder, resistance welding, wire wrap, and crimped connections, a few reliability reports were received on other connection types. However, the data was not in large enough quantity to result in a meaningful

analyses. Therefore, it is recommended that further effort be directed toward collecting reliability reports on ultrasonic welding, thermal compression bonding, gallium alloy, and gold foil connection types. Failure rate estimates of these types added to those calculated in this study should result in a more complete spectrum of the reliability characteristics of the major connection types now available.

6.3 Controlled Tests

The second objective of the study program was to measure the effects of various environmental stresses on connection failure rates. In general, the reliability reports that were obtained were not complete enough in their descriptions of environmental operating conditions to enable the desired relationships to be established. Had it been possible to measure the effects of environmental stresses much would have been gained. However it appears that the environmental effects can best be measured under controlled conditions.

Therefore, it is recommended that the effects of environmental stresses on connection failure rates be studied through a series of controlled tests. The most efficient way of evaluating several environmental effects in the same series of tests is to perform a factorial experiment. A typical example of such an experiment is shown below:

Temperature \ Vibration	V1	V2	V3
T1			
T2			
T3			

In the example symbolized above, each cell would be filled with a failure rate generated in a controlled test performed under the combined environments of temperature and vibration. Each environment level should be judiciously selected over the entire range of expected operating conditions. The results of such a series of experiments would be the effect of temperature on failure rate, the effect of vibration on failure rate, the effect of vibration and temperature interaction, and an estimate of the unexplained variation. One of the combined environments placed on the test in the factorial experiment would be with both temperature and vibration at relatively mild stress levels. Therefore, a test of this nature might be of relatively long duration.

Since the failure rates which have been calculated for the various connection types are small, a rather large number of operating hours and observations of failures would be required to obtain good estimates of the effects of environmental stresses on connections. The accumulation of a sufficient number of connection operating hours in a reasonable calendar time can be accomplished by using large sample sizes in each of the cells of the factorial experiment. An example of a type of controlled test that could be run would be testing of solder connections on circuit boards. Each board could accomodate from 150 to 200 solder joints and a sufficient number could be

tested in each combined environment to observe several failures during a period of one calendar year. The total number of environments and stress levels to be included in the test would be subjects for study in order that the ones included in the study program were those most likely to affect the reliability of connections.

6.4 Merit Index Refinement

The Merit Index developed during this study appears to be a reasonable step toward simplifying an extremely complex decision making process. The factors included in the Merit Index are not the only ones to be considered. For example, cost is one that is extremely important and one that presents many difficulties. It cannot be omitted from a designer's decision when specifying a type of connection. Additional study is required to incorporate the cost factor into the index.

The quantification of sub-factors completed in this report applies mainly to solder, resistance weld, wire wrap, and crimp connections. The point ratings and the connection attributes developed ideally should be applicable to most connection types. Actually, they were heavily influenced by the four types mentioned.

The recommendation, therefore, is that additional effort be applied to refine the Merit Index, to expand its versatility to other connection types, and to increase its discriminatory power by the inclusion of additional factors.

6.5 Merit Index Validation

The final test of the utility of a tool is whether or not it actually performs the job for which it was designed. The Merit Index presently stands as a tool that has been developed, but untried. Validation is still required. It is recommended that it be tested by presenting the index to a select group of design engineers and to a select group of service personnel for their trial use. Their opinions and comments, properly classified and analyzed, will provide partial validation of the accuracy and acceptance of the Merit Index as a tool.

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APPENDIX I

FAILURE RATE DATA

This appendix contains three tabular listings. The first, Table I-1, enumerates the environments that, in the researchers' opinions, are the ones most likely to affect connection failure rate. The high, medium, and low stress intervals were developed from the study of various military specifications, designers reliability handbooks, and other technical publications, as well as on the judgement and experience of the researchers. Table I-2 gives a brief description of the types of equipment and the types of laboratory tests for which data was available. Table I-3 is a summary of the data collected during this study. The data are grouped in connection types and sub-grouped by the type of equipment and laboratory test in which the connection is used. Sub-totals are given for each type of equipment and laboratory test. Grand totals are given for each type of connection. The symbols H (high), M (medium), and L (low) are used to describe each reliability report received during the data search phase of the study.

TABLE I-1 Environmental Stress Levels

Corrosive Agent	Low (L) No Corrosive Agent Present	Medium (M) Mild Corrosive Agent Present	High (H) Severe Corrosive Agent Present
Temperature Cycle (^oC/Minute)	0 - 2	2 - 5	above 5
Humidity (%)	0 - 50	50 - 80	80 - 100
Shock (g's)	0 - 5	5 - 40	above 40
Vibration (CPS) (g's)	0 - 10 0 - 2	10 - 100 2 - 5	above 100 above 5
Static Mechanical (lb.)	0 - 1	1 - 4	above 4

TABLE I-2 Types of Equipment

Equipment Classes	Description
1. Ground Computers	stationary and mobile computers with controlled or uncontrolled environments
2. General Ground Equipment	all other stationary and mobile ground equipment with controlled or uncontrolled environments
3. Shipboard	all equipment mounted on board submarine or surface vessels
4. Ground Radars	stationary and mobile radars with controlled or uncontrolled environments
5. Airborne	all equipment mounted in aircraft, missiles and satellites
6. Laboratory tests on Vacuum Tubes	connections contained in Vacuum Tubes
7. Laboratory Tests on connections	special tests configurations which contain only connections
8. Laboratory test on modules, cards, parts	production items with connections between components

TABLE I-3 Summary of Reliability Reports Received

SOLDERED CONNECTIONS						Environmental Stress				
	Joint-Hours of Operation x10^8	Number of Failures	Failure Rate (%/1000 Hrs.)	90% Confidence Interval (% /1000 Hrs.)	60% Confidence Interval (% /1000 Hrs.)	Corrosive Agent	Temperature Cycle	Humidity	Shock	Vibration
LAB. TESTS (MODULES, CARDS, PARTS)										
	0.0138	0	-	0 - 0.17	0 - 0.066	L	L	L	L	L
	0.00623	0	-	0 - 0.37	0 - 0.15	L	M	L	L	L
	0.0451	3	0.067	0.018 - 0.14	0.034 0.095	L	M	L	L	L
	8.36	0	-	0 - 0.0028	0 - 0.0011	L	L	L	L	H
	0.596	4	0.0067	0.0023 - 0.0130	0.0039 - 0.0092	L	L	L	L	H
	0.000548	13	24.	14. - 36.	18. - 29.	L	M	L	L	L
	0.0205	237	12.	10. - 13.	11. - 12.	L	M	L	L	H
	0.00251	8	3.2	1.6 - 5.2	2.2 - 4.1	L	M	L	L	H
	0.0138	34	2.5	1.8 - 3.2	2.1 - 2.8	L	M	L	L	L
	0.000936	3	3.2	0.88 - 6.7	1.6 - 4.6	L	M	L	L	L
	0.0142	57	4.0	3.2 - 4.9	3.6 - 4.5	L	M	L	L	L
	0.0596	2	0.034	0.0060 - 0.080	0.014 - 0.050	L	M	L	L	M
	0.001096	18	16.	11. - 23.	13. - 20.	L	M	L	L	L
	0.0102	10	0.98	0.53 - 1.5	0.72 - 1.2	L	L	L	L	H

TABLE I-3 Summary of Reliability Reports Received (Cont.)

SOLDERED CONNECTIONS (Cont'd)					Environmental Stress				
Joint-Hours of Operation x10^8	Number of Failures	Failure Rate (%/1000 Hrs.)	90% Confidence Interval (%/1000 Hrs.)	60% Confidence Interval (%/1000 Hrs.)	Corrosive Agent	Temperature Cycle	Humidity	Shock	Vibration
0.00321	2	0.62	0.11 - 1.5	0.26 - 0.93	L	M	L	L	H
0.00125	4	3.2	1.1 - 6.2	1.8 - 4.4	L	M	L	L	H
0.0156	0	-	0 - 0.15	0 - 0.059	L	M	L	L	L
0.0269	11	0.41	0.23 - 0.63	0.30 - 0.57	L	M	L	L	L
0.00330	2	0.61	0.11 - 1.4	0.25 - 0.91	L	M	L	L	L
0.0256	0	-	0 - 0.090	0 - 0.036	L	M	L	L	H
0.00129	0	-	0 - 1.8	0 - 0.71	L	L	L	L	L
0.0578	0	-	0 - 0.040	0 - 0.016	L	M	L	L	L
0.00463	0	-	0 - 0.50	0 - 0.20	L	M	L	L	M
0.00125	0	-	0 - 1.8	0 - 0.73	L	M	L	L	H
0.00780	5	0.64	0.25 - 1.2	0.40 - 0.86	L	M	L	L	L
0.00702	10	1.4	0.78 - 2.3	1.0 - 1.8	L	M	L	L	L
0.00429	18	4.2	2.7 - 5.9	3.3 - 5.0	L	M	L	L	L
0.00831	19	2.3	1.5 - 3.2	1.8 - 2.7	L	M	L	L	L
0.0119	3	0.25	0.069 - 0.53	0.13 - 0.36	L	M	L	L	M
0.234	1	0.0043	0.00022 - 0.013	0.00095 - 0.0069	L	M	L	L	L

TABLE I-3 Summary of Reliability Reports Received (Cont.)

SOLDERED CONNECTIONS (Cont'd)						Environmental Stress				
	Joint-Hours of Operation x10^8	Number of Failures	Failure Rate (%/1000 Hrs.)	90% Confidence Interval (%/1000 Hrs.)	60% Confidence Interval (%/1000 Hrs.)	Corrosive Agent	Temperature Cycle	Humidity	Shock	Vibration
	0.361	3	0.0083	0.0023 - 0.018	0.0043 - 0.012	L	M	L	L	M
	0.446	0	-	0 - 0.0052	0 - 0.0021	L	L	L	L	M
	0.0280	0	-	0 - 0.083	0 - 0.033	L	L	L	L	M
	0.127	0	-	0 - 0.018	0 - 0.0072	L	L	L	L	M
	0.220	0	-	0 - 0.011	0 - 0.0042	L	L	L	L	M
	0.00384	0	-	0 - 0.60	0 - 0.24	L	L	L	L	H
	0.0731	1	0.014	0.00071 - 0.041	0.0031 - 0.022	L	M	L	L	L
	6.45	0	-	0 - 0.00036	0 - 0.00014	L	L	L	L	L
	0.19	9	0.047	0.025 - 0.076	0.034 - 0.063	L	H	L	L	L
	0.149	22	0.15	0.10 - 0.20	0.12 - 0.17	L	H	L	H	H
	0.767	0	-	0 - 0.0030	0 - 0.0012	L	L	L	L	L
	0.000255	0	-	0 - 9.0	0 - 3.6	L	M	L	H	H
	0.018	0	-	0 - 0.13	0 - 0.051	L	L	L	L	M
Subtotal	18.39	499	0.027	0.025 - 0.029	0.026 - 0.028					

TABLE I-3 Summary of Reliability Reports Received (Cont.)

SOLDERED CONNECTIONS (Cont'd)						Environmental Stress				
	Joint-Hours of Operation $\times 10^8$	Number of Failures	Failure Rate (%/1000 Hrs.)	90% Confidence Interval (%/1000 Hrs.)	60% Confidence Interval (%/1000 Hrs.)	Corrosive Agent	Temperature Cycle	Humidity	Shock	Vibration
LAB. TESTS (CONNECTIONS)										
	0.0453	1	0.022	0.0011 - 0.066	0.0051 - 0.036	L	M	L	L	L
	0.0508	0	-	0 - 0.045	0 - 0.018	L	L	L	L	L
	0.0007	0	-	0 - 3.3	0 - 1.3	L	M	L	L	L
	0.0004	0	-	0 - 7.7	0 - 3.1	L	H	L	L	L
Subtotal	0.0972	1	0.010	0.00053 - 0.031	0.0023 - 0.017					
GROUND EQUIPMENT (EXCEPT RADARS, COMPUTERS)										
	0.0574	5	0.087	0.034 - 0.16	0.054 - 0.12	L	L	L	H	M
	0.120	0	-	0 - 0.019	0 - 0.0077	L	M	H	L	L
	0.411	0	-	0 - 0.0056	0 - 0.0022	L	L	L	L	L
	3.80	5	0.0013	0.00052 - 0.0024	0.00081 - 0.0018	M	M	M	M	M
	18.3	36	0.0020	0.0015 - 0.0025	0.0017 - 0.0022	M	M	M	M	M
	7.79	32	0.0041	0.0030 - 0.0054	0.0035 - 0.0047	M	M	M	M	M
	1.49	0	-	0 - 0.0016	0 - 0.00062	L	L	L	L	L

TABLE I-3 Summary of Reliability Reports Received (Cont.)

SOLDERED CONNECTIONS (Cont'd)						Environmental Stress				
	Joint-Hours of Operation x10⁸	Number of Fail-ures	Failure Rate (%/1000 Hrs.)	90% Confidence Interval (%/1000 Hrs.)	60% Confidence Interval (%/1000 Hrs.)	Corrosive Agent	Temperature Cycle	Humidity	Shock	Vibration
	120.	0	-	0 - 0.000019	0 - 0.0000075	L	L	L	L	L
	21.15	24	0.0011	0.00078 - 0.0015	0.00094 - 0.0013	L	L	L	L	L
	0.199	0	-	0 - 0.012	0 - 0.0046	L	L	L	L	L
	1.545	0	-	0 - 0.0015	0 - 0.00059	-	-	-	-	-
	6.15	0	-	0 - 0.00038	0 - 0.00015	L	L	L	L	
Subtotal	179.5	102	0.00057	0.00048 - 0.00067	0.00052 - 0.00062					
GROUND RADARS										
	0.323	0	-	0 - 0.0071	0 - 0.0028	M	M	M	M	M
	0.434	0	-	0 - 0.0053	0 - 0.0021	L	L	L	L	L
	0.649	2	0.0031	0.00055 - 0.0073	0.0013 - 0.0046	L	L	L	L	L
Subtotal	1.40	2	0.0014	0.00025 - 0.0034	0.00059 - 0.0021					
GROUND COMPUTERS										
	2.60	3	0.0012	0.00032 - 0.0024	0.00059 - 0.0017	M	M	M	M	M
	8.29	9	0.0011	0.00057 - 0.0017	0.00078 - 0.0014	M	H	M	M	M
	36.9	4	0.0011	0.000037 - 0.00021	0.000062 - 0.00015	L	L	L	L	L

TABLE I-3 Summary of Reliability Reports Received (Cont.)

SOLDERED CONNECTIONS (Cont'd)						Environmental Stress				
	Joint-Hours of Operation $\times 10^8$	Number of Failures	Failure Rate (%/1000 Hrs.)	90% Confidence Interval (%/1000 Hrs.)	60% Confidence Interval (%/1000 Hrs.)	Corrosive Agent	Temperature Cycle	Humidity	Shock	Vibration
	1.18	0	-	0 - 0.0020	0 - 0.00078	L	L	L	L	L
	31.2	2	0.000064	0.000011 - 0.00015	0.000016 - 0.000096	L	L	L	L	L
	393.6	88	0.00022	0.00019 - 0.00026	0.00020 - 0.00024	L	L	L	L	L
	5.15	4	0.00078	0.00027 - 0.0015	0.00045 - 0.0012	L	L	L	L	L
	2.62	18	0.0069	0.0044 - 0.0090	0.0055 - 0.0082	L	L	L	L	L
	11.53	32	0.0028	0.0021 - 0.0036	0.0024 - 0.0032	L	L	L	L	L
	6.57	15	0.0023	0.0014 - 0.0033	0.0018 - 0.0028	L	M	L	M	M
	5.73	29	0.0051	0.0036 - 0.0067	0.0043 - 0.0058	L	L	L	L	L
	0.729	3	0.0041	0.0011 - 0.0086	0.0021 - 0.0059	L	L	L	L	L
	0.881	0	-	0 - 0.0026	0 - 0.0010	L	L	L	L	L
	0.173	0	-	0 - 0.013	0 - 0.0053	M	M	M	M	M
	0.954	0	-	0 - 0.0024	0 - 0.00096	L	L	L	L	L
	1.47	0	-	0 - 0.0016	0 - 0.00062	L	L	L	L	L
	1.155	0	-	0 - 0.0020	0 - 0.00079	L	L	L	L	L
	10.54	0	-	0 - 0.00022	0 - 0.000037	L	L	L	M	M
Subtotal	521.3	207	0.00040	0.00035 - 0.00044	0.00037 - 0.00042					

TABLE I-3 Summary of Reliability Reports Received (Cont.)

SOLDERED CONNECTIONS (Cont'd)									
					Environmental Stress				
Joint-Hours of Operation x108	Number of Fail-ures	Failure Rate (%/1000 Hrs.)	90% Confidence Interval (%/1000 Hrs.)	60% Confidence Interval (%/1000 Hrs.)	Corrosive Agent	Temperature Cycle	Humidity	Shock	Vibration
AIRBORNE EQUIPMENT									
1.27	10	0.0079	0.0043 - 0.012	0.0058 - 0.0098	M	H	M	M	M
1.63	3	0.0018	0.00050 - 0.0039	0.00094 - 0.0026	M	H	M	M	M
4.33	13	0.0030	0.0018 - 0.0045	0.0023 - 0.0037	M	H	M	M	M
10.3	5	0.00049	0.00019 - 0.00089	0.00030 - 0.00065	M	H	M	M	M
0.102	1	0.0098	0.00051 - 0.029	0.0022 - 0.016	M	H	M	M	M
9.11	1	0.00011	0.0000057 - 0.00033	0.000025 - 0.00018	L	L	L	H	H
0.00583	1	0.17	0.0088 - 0.54	0.038 - 0.28	L	M	L	H	H
0.048	1	0.021	0.0011 - 0.062	0.0046 - 0.034	L	L	L	H	H
0.00476	1	0.21	0.011 - 0.63	0.047 - 0.34	L	L	L	H	H
0.974	76	0.078	0.064 - 0.093	0.070 - 0.086	L	M	M	M	M
0.00153	0	-	0 - 1.5	0 - 0.60	L	L	L	H	H
0.132	0	-	0 - 0.018	0 - 0.0070	L	M	L	M	M
0.132	0	-	0 - 0.018	0 - 0.0070	L	M	L	M	M
0.0456	0	-	0 - 0.051	0 - 0.020	L	L	L	H	H
0.423	0	-	0 - 0.0055	0 - 0.0022	L	L	L	H	H

TABLE I-3 Summary of Reliability Reports Received (Cont.)

SOLDERED CONNECTIONS (Cont'd)										
	Joint-Hours of Operation $\times 10^8$	Number of Failures	Failure Rate (%/1000 Hrs.)	90% Confidence Interval (%/1000 Hrs.)	60% Confidence Interval (%/1000 Hrs.)	Environmental Stress: Corrosive Agent	Temperature Cycle	Humidity	Shock	Vibration
	1.16	0	-	0 - 0.0020	0 - 0.00079	L	M	L	L	L
	1.46	0	-	0 - 0.0016	0 - 0.00063	L	H	L	L	L
	*	*	0.02	-	-	H	H	L	H	H
Subtotal	29.86	102	0.0034	0.0029 - 0.0040	0.0031 - 0.0037					
* Not Given										
SHIPBOARD EQUIPMENT										
	0.03C28	0	-	0 - 0.076	0 - 0.030	L	L	L	H	H
	14.96	9	0.00060	0.00031 - 0.00097	0.00043 - 0.00076	M	M	H	L	L
	1.01	5	0.0050	0.0020 - 0.0091	0.0031 - 0.0066	L	L	H	L	M
	0.405	0	-	0 - 0.0057	0 - 0.0023	L	L	L	L	L
Subtotal	16.40	14	0.00085	0.00052 - 0.0013	0.00067 - 0.0011					
SOLDERED GRAND TOTAL										
	766.9	927	0.0012	0.0011 - 0.0013	0.0012 - 0.0012					

TABLE I-3 Summary of Reliability Reports Received (Cont.)

WELDED CONNECTIONS						Environmental Stress					
	Joint-Hours of Operation x 10^8	Number of Failures	Failure Rate (%/1000 Hrs.)	90% Confidence Interval (%/1000 Hrs.)	60% Confidence Interval (%/1000 Hrs.)	Corrosive Agent	Temperature-Cycle	Humidity	Shock	Vibration	Mechanical Static
<u>LAB TESTS</u> (MODULES, CARDS, PARTS)											
	0.145	0	-	0 - 0.16	0 - 0.0083	L	L	L	L	L	L
	0.0000935	0	-	0 - 25.	0 - 9.8	L	M	L	H	H	L
	0.00036	0	-	0 - 6.4	0 - 2.5	L	H	L	L	L	L
	0.00036	0	-	0 - 6.4	0 - 2.5	L	H	L	L	L	L
	0.00036	0	-	0 - 6.4	0 - 2.5	L	H	L	L	L	L
	0.00036	0	-	0 - 6.4	0 - 2.5	L	H	L	L	L	L
	0.00036	0	-	0 - 6.4	0 - 2.5	L	H	L	L	L	L
	0.00036	0	-	0 - 6.4	0 - 2.5	L	H	L	L	L	L
	0.0007	0	-	0 - 3.3	0 - 1.3	L	H	L	L	L	L
	0.00365	0	-	0 - 0.63	0 - 0.25	L	L	L	L	L	H
	0.00353	1	0.28	0.015 - 0.85	0.063 - 0.46	L	L	L	L	L	M
	0.00365	1	0.27	0.014 - 0.82	0.064 - 0.44	L	L	L	L	L	M
	0.00372	0	-	0 - 0.62	0 - 0.25	L	L	L	L	L	M
	0.00365	3	0.82	0.23 - 1.7	0.42 - 1.2	L	L	L	L	L	M
	0.00358	0	-	0 - 0.64	0 - 0.26	L	L	L	L	L	H

TABLE I-3 Summary of Reliability Reports Received (Cont.)

WELDED CONNECTIONS (Cont'd)					Environmental Stress					
Joint-Hours of Operation x 10^8	Number of Fail-ures	Failure Rate (%/1000 Hrs.)	90% Confidence Interval (%/1000 Hrs.)	60% Confidence Interval (%/1000 Hrs.)	Corrosive Agent	Temperature Cycle	Humidity	Shock	Vibration	Mechanical Static
0.00384	0	-	0 - 0.60	0 - 0.24	L	L	L	L	L	M
0.00384	0	-	0 - 0.60	0 - 0.24	L	L	L	L	L	M
0.00384	0	-	0 - 0.60	0 - 0.24	L	L	L	L	L	M
0.00229	1	0.44	0.0223 - 1.3	0.097 - 0.70	L	L	L	L	L	M
0.0035	0	-	0 - 0.66	0 - 0.26	L	L	L	L	L	M
0.00365	0	-	0 - 0.63	0 - 0.25	L	L	L	L	L	H
0.00355	0	-	0 - 0.65	0 - 0.26	L	L	L	L	L	M
0.00353	0	-	0 - 0.65	0 - 0.26	L	L	L	L	L	M
0.00353	0	-	0 - 0.65	0 - 0.26	L	L	L	L	L	M
0.00358	0	-	0 - 0.64	0 - 0.26	L	L	L	L	L	M
0.00365	0	-	0 - 0.63	0 - 0.25	L	L	L	L	L	H
0.00382	2	0.52	0.093 - 1.2	0.22 - 0.78	L	L	L	L	L	H
0.0356	0	-	0 - 0.065	0 - 0.026	L	L	L	L	L	M
0.00384	0	-	0 - 0.60	0 - 0.24	L	L	L	L	L	M
0.00353	0	-	0 - 0.65	0 - 0.26	L	L	L	L	L	M
0.00367	0	-	0 - 0.63	0 - 0.25	L	L	L	L	L	M
0.00385	1	0.28	0.014 - 0.34	0.062 - 0.45	L	L	L	L	L	H

TABLE I-3 Summary of Reliability Reports Received (Cont.)

	Joint-Hours of Operation x 10^8	Number of Failures	Failure Rate (%/1000 Hrs.)	90% Confidence Interval (%/1000 Hrs.)	60% Confidence Interval (%/1000 Hrs.)	Environmental Stress: Corrosive Agent	Temperature Cycle	Humidity	Shock	Vibration	Mechanical Static
WELDED CONNECTIONS (Cont'd)											
	0.00336	0	-	0 - 0.69	0 - 0.27	L	L	L	L	L	M
	0.0127	3	0.24	0.065 - 0.50	0.12 - 0.34	L	L	L	L	L	H
	0.0171	2	0.12	0.021 - 0.28	0.048 - 0.18	L	L	L	L	L	H
	0.0181	0	-	0 - 0.13	0 - 0.051	L	L	L	L	L	H
	0.00336	0	-	0 - 0.69	0 - 0.27	L	L	L	L	L	H
	0.0042	0	-	0 - 0.55	0 - 0.22	L	L	L	L	L	H
	0.00885	0	-	0 - 0.26	0 - 0.10	L	L	L	L	L	H
	0.00451	0	-	0 - 0.51	0 - 0.20	L	L	L	L	L	H
	0.065	0	-	0 - 0.033	0 - 0.013	M	L	H	L	L	L
Subtotal	0.372	14	0.038	0.023 - 0.056	0.029 - 0.046						
GROUND EQUIPMENT (EXCEPT RADARS, COMPUTERS)											
	0.0591	0	-	0 - 0.039	0 - 0.016	L	L	L	L	L	L
	2.99	0	-	0 - 0.00077	0 - 0.00031	L	L	L	L	L	L
	0.606	0	-	0 - 0.0038	0 - 0.0015	L	L	L	L	L	L

TABLE I-3 Summary of Reliability Reports Received (Cont.)

WELDED CONNECTIONS (Cont'd)						Environmental Stress					
	Joint-Hours of Operation x 10^8	Number of Failures	Failure Rate (%/1000 Hrs.)	90% Confidence Interval (%/1000 Hrs.)	60% Confidence Interval (%/1000 Hrs.)	Corrosive Agent	Temperature Cycle	Humidity	Shock	Vibration	Mechanical Static
	0.164	2	0.012	0.0022 - 0.029	0.0050 - 0.018	L	M	L	L	L	L
	6.90	0	-	0 - 0.00033	0 - 0.00013	L	L	L	L	L	L
Subtotal	10.72	2	0.00019	0.000033 - 0.00044	0.000077 - 0.00028						
AIRBORNE EQUIPMENT											
	0.0736	0	-	0 - 0.031	0 - 0.013	L	M	L	L	L	L
	0.682	6	0.0088	0.0038 - 0.015	0.0057 - 0.012	M	H	H	H	H	L
Subtotal	0.756	6	0.0079	0.0035 - 0.014	0.0052 - 0.010						
INTERNAL CONNECTIONS (WITHIN VACUUM TUBES)											
	0.9	2	0.0022	0.00040 - 0.0053	0.00092 - 0.0033	L	M	L	L	L	L
	0.35	1	0.0029	0.00015 - 0.0086	0.00064 - 0.0046	L	M	L	L	L	L
	0.00044	0	-	0 - 5.2	0 - 2.1	L	L	L	H	L	L

TABLE I-3 Summary of Reliability Reports Received (Cont.)

WELDED CONNECTIONS (Cont'd)

	Joint-Hours of Operation x 10^8	Number of Failures	Failure Rate (%/1000 Hrs.)	90% Confidence Interval (%/1000 Hrs.)	60% Confidence Interval (%/1000 Hrs.)	Environmental Stress: Corrosive Agent	Temperature Cycle	Humidity	Shock	Vibration	Mechanical Static
	0.39	0	-	0 - 0.059	0 - 0.024	L	L	L	H	H	L
	0.00059	0	-	0 - 3.9	0 - 1.6	L	L	L	H	H	L
Subtotal	1.64	3	0.0018	0.00050 - 0.0038	0.00094 - 0.0026						
WELDED GRAND TOTAL	13.49	25	0.0019	0.0013 - 0.0025	0.0015 - 0.0022						

TABLE I-3 Summary of Reliability Reports Received (Cont.)

WIRE WRAP CONNECTIONS						Environmental Stress				
	Joint Hours of Operation $\times 10^8$	Number of Failures	Failure Rate (%/1000 Hrs.)	90% Confidence Interval (%/1000 Hrs.)	60% Confidence Interval (%/1000 Hrs.)	Corrosive Agent	Temperature Cycle	Humidity	Shock	Vibration
LAB. TESTS (CONNECTIONS)										
	0.0014	0	-	0 - 1.7	0 - 0.65	L	M	L	H	H
	0.00368	0	-	0 - 0.63	0 - 0.25	H	M	H	L	M
	0.00328	0	-	0 - 0.70	0 - 0.28	H	M	H	L	M
	0.00328	0	-	0 - 0.70	0 - 0.28	H	M	H	L	M
	0.00328	0	-	0 - 0.70	0 - 0.28	H	M	H	L	M
	0.00736	0	-	0 - 0.31	0 - 0.12	H	M	H	L	M
	0.00164	25	15	11 - 21	13 - 18	H	M	H	L	L
	0.00192	5	2.6	1.0 - 4.8	1.6 - 3.5	H	M	H	L	L
	0.00192	1	0.52	0.027 - 1.6	0.12 - 0.84	H	M	H	L	L
	0.00192	0	-	0 - 1.2	0 - 0.48	H	M	H	L	L
	0.00658	0	-	0 - 0.35	0 - 0.14	H	M	H	L	L
	0.00164	0	-	0 - 1.4	0 - 0.56	L	L	H	L	L
	0.00131	0	-	0 - 1.8	0 - 0.70	L	L	H	L	L
	0.00164	0	-	0 - 1.4	0 - 0.56	L	L	H	L	L
	0.000146	0	-	0 - 16	0 - 6.3	H	M	H	L	M

TABLE I-3 Summary of Reliability Reports Received (Cont.)

WIRE WRAP CONNECTIONS (Cont'd)						Environmental Stress				
	Joint Hours of Operation $\times 10^8$	Number of Failures	Failure Rate (%/1000 Hrs.)	90% Confidence Interval (%/1000 Hrs.)	60% Confidence Interval (%/1000 Hrs.)	Corrosive Agent	Temperature Cycle	Humidity	Shock	Vibration
	0.000146	0	-	0 - 16	0 - 6.3	H	M	H	L	M
	0.000146	0	-	0 - 16	0 - 6.3	H	M	H	L	M
	0.000146	0	-	0 - 16	0 - 6.3	H	M	H	L	M
	0.000146	0	-	0 - 16	0 - 6.3	H	M	H	L	M
	0.000183	0	-	0 - 13	0 - 5.0	H	M	H	L	M
	0.0131	0	-	0 - 0.18	0 - 0.070	H	M	H	L	M
	0.000365	0	-	0 - 6.3	0 - 2.5	H	M	H	L	L
	0.000365	0	-	0 - 6.3	0 - 2.5	H	M	H	L	L
	0.000730	0	-	0 - 3.2	0 - 1.3	L	M	H	L	L
	0.000475	0	-	0 - 4.9	0 - 1.9	H	M	H	L	L
	0.000475	0	-	0 - 4.9	0 - 1.9	H	M	H	L	L
	0.00238	0	-	0 - 0.97	0 - 0.38	H	M	H	L	L
	0.00219	0	-	0 - 1.1	0 - 0.42	H	M	H	L	L
	0.00219	0	-	0 - 1.1	0 - 0.42	H	M	H	L	L
	0.00219	0	-	0 - 1.1	0 - 0.42	H	M	H	L	L
	0.00219	0	-	0 - 1.1	0 - 0.42	H	M	H	L	L
Subtotal	0.0684	31	0.45	0.33 - 0.59	0.38 - 0.52					

TABLE I-3 Summary of Reliability Reports Received (Cont.)

WIRE WRAP CONNECTIONS (Cont'd)						Environmental Stress				
	Joint Hours of Operation x10^8	Number of Fail-ures	Failure Rate (%/1000 Hrs.)	90% Confidence Interval (%/1000 Hrs.)	60% Confidence Interval (%/1000 Hrs.)	Corrosive Agent	Temperature Cycle	Humidity	Shock	Vibration
GROUND COMPUTERS										
	1350.	1	0.00000074	0.000000038 - 0.0000022	0.00000017 - 0.0000012	L	L	L	L	L
	14.55	0	-	0 - 0.00016	0 - 0.000063	L	L	L	L	L
	1340.	0	-	0 - 0.0000017	0 - 0.00000068	L	L	L	L	L
Subtotal	2704.55	1	0.00000037	0.000000019 - 0.0000011	0.000000083 - 0.00000060	L	L	L	L	L
AIRBORNE EQUIPMENT										
	0.5	0	-	0 - 0.0046	0 - 0.0018	M	H	M	H	H
WIRE WRAP GRAND TOTAL	2705.12	32	0.000012	0.0000086 - 0.000015	0.000010 - 0.000014					

TABLE I-3 Summary of Reliability Reports Received (Cont.)

CRIMPED CONNECTIONS										
						Environmental Stress				
	Joint-Hours of Operation x 10^8	Number of Fail-ures	Failure Rate (% /1000 Hrs.)	90% Confidence Interval (% /1000 Hrs.)	60% Confidence Interval (% /1000 Hrs.)	Corrosive Agent	Temperature Cycle	Humidity	Shock	Vibration
LAB TESTS (CONNECTIONS)										
	0.00012	0	-	0 - 20	0 - 7.9	L	H	H	L	L
Subtotal	0.00012	0	-	0 - 20	0 - 7.9					
GROUND COMPUTERS										
	0.0928	0	-	0 - 0.025	0 - 0.0099	L	L	L	L	L
	0.847	1	0.0012	0.000061 - 0.0035	0.00026 - 0.0020	L	L	L	M	M
	0.528	3	0.0057	0.0016 - 0.012	0.0029 - 0.0081	L	M	L	M	M
	0.104	0	-	0 - 0.022	0 - 0.0089	L	L	L	L	L
	0.134	0	-	0 - 0.017	0 - 0.0068	L	L	L	L	L
	0.414	1	0.0024	0.00012 - 0.0072	0.00054 - 0.0039	L	L	L	L	L
	0.0422	0	-	0 - 0.055	0 - 0.022	L	L	L	H	M
	0.0880	0	-	0 - 0.026	0 - 0.010	L	M	H	L	L
	0.302	0	-	0 - 0.0076	0 - 0.0031	L	L	L	L	L

TABLE I-3 Summary of Reliability Reports Received (Cont.)

CRIMPED CONNECTIONS (Cont'd)						Environmental Stress				
	Joint-Hours of Operation x 10^8	Number of Failures	Failure Rate (%/1000 Hrs.)	90% Confidence Interval (%/1000 Hrs.)	60% Confidence Interval (%/1000 Hrs.)	Corrosive Agent	Temperature Cycle	Humidity	Shock	Vibration
	1.10	0	-	0 - 0.0021	0 - 0.00083	L	L	L	L	L
	0.0800	1	0.011	0.00057 - 0.033	0.0026 - 0.018	M	M	M	M	M
Subtotal	3.73	6	0.0016	0.00070 - 0.0028	0.0010 - 0.0021					
AIRBORNE EQUIPMENT	*	*	0.00087	-	-	H	H	H	H	H
CRIMPED CONNECTIONS GRAND TOTAL	3.73	6	0.0016	0.00070 - 0.002^	0.0010 - 0.0021					

*Not Given

TABLE I-3 Summary of Reliability Reports Received (Cont.)

ULTRASONIC WELDED CONNECTORS						Environmental Stress				
	Joint-Hours of Operation x 10^8	Number of Failures	Failure Rate (%/1000 Hrs.)	90% Confidence Interval (%/1000 Hrs.)	60% Confidence Interval (%/1000 Hrs.)	Corrosive Agent	Temperature Cycle	Humidity	Shock	Vibration
LAB TESTS (CONNECTIONS)										
	0.00036	0	-	0 - 6.4	0 - 2.5	L	H	L	L	L
	0.00036	0	-	0 - 6.4	0 - 2.5	L	H	L	L	L
	0.00036	0	-	0 - 6.4	0 - 2.5	L	H	L	L	L
	0.0008	0	-	0 - 2.9	0 - 1.1	L	H	L	L	L
	0.0014	0	-	0 - 1.7	0 - 0.65	L	H	L	L	L
ULTRASONIC GRAND TOTAL	0.00328	0	-	0 - 0.70	0 - 0.29					
THERMAL COMPRESSION BONDING										
	Joint-Hours of Operation x 10^8	Number of Failures	Failure Rate (%/1000 Hrs.)	90% Confidence Interval (%/1000 Hrs.)	60% Confidence Interval (%/1000 Hrs.)					
LAB TESTS (CONNECTIONS)										
	5.10	0	-	0 - 0.00045	0 - 0.00018	-	-	-	-	-

APPENDIX II

CALCULATION OF CONFIDENCE INTERVALS*

A confidence interval at some level $1 - \alpha$ gives, the interval in which the failure rate will be contained with probability $1 - \alpha$.

C_L = one-sided lower confidence limit

$1 - \frac{\alpha}{2}$ = upper confidence limit

$\frac{\alpha}{2}$ = lower confidence limit

X^2 = Chi-square

r = Number of failures

$\hat{m}$ = Estimated MTBF $\qquad \hat{m} = \frac{T}{r}$

m = True MTBF

T = Number of joint — hours of operation

Two sided confidence interval

$$\frac{2r\hat{m}}{X^2_{(\frac{\alpha}{2};\, 2r)}} \leq m \leq \frac{2r\hat{m}}{X^2_{(1 - \frac{\alpha}{2};\, 2r)}}$$

Confidence interval — no failure observed

$$C_L = \frac{2T}{X^2_{(\alpha;\, 2)}}$$

*Igor Bazovsky, Reliability: Theory and Practice, Prentice Hall, Inc., Englewood Cliffs, New Jersey, 1961, p. 235 - 238.

APPENDIX III

TESTS OF THE EQUALITY OF 2 MTBF

In this study it was often necessary to test hypotheses concerning connection MTBF's. For example it was desired to test:

$H_0 : m_W = m_S$

versus

$H_1 : m_W \neq m_S$

Where m_W is the true MTBF of welded connections and m_S is the true MTBF of soldered joints.

The method used was the F-test developed below.

It is known that:

$$U_W = \frac{2R_W \hat{m}_W}{m_W}$$ is distributed as X^2 with $2R_W$ degrees of freedom,

and

$$U_S = \frac{2R_S \hat{m}_S}{m_S}$$ is similarly distributed.

Here R_S and R_W are the numbers of observed failures and $\hat{m}_S$ and $\hat{m}_W$ are the sample MTBF. Now, since U_W and U_S are distributed as X^2, then under the hypothesis $m_W = m_S$ the ratio

$$R = \frac{U_W/ 2R_W}{U_S/2R_S} = \frac{\hat{m}_W/ m_W}{\hat{m}_S/ m_S} = \frac{\hat{m}_W}{\hat{m}_S}$$

is distributed as $F_{(2R_W,\ 2R_S)}$ and a significance test can be made using the ratio R and the F tables with the appropriate .

APPENDIX IV MULTIPLE REGRESSION DATA AND RESULTS

The raw data used in the 7 linear multiple regression analyses are presented on the following pages. All required calculations were performed on an IBM 7094 computer; the results are presented under their respective heading for each problem.

Problem 1 — Solder Joints Using Point Estimates

Measured Observations:

	Failure Rate (%/1000 hrs.)	Temperature	Humidity	Vibration
1	.00115	2.	2.	2.
2	.08710	1.	1.	2.
3	.06650	2.	1.	1.
4	.00787	3.	2.	2.
5	.00109	3.	2.	2.
6	.00184	3.	2.	2.
7	.00300	3.	2.	2.
8	.00049	3.	2.	2.
9	.00980	3.	2.	2.
10	.00011	1.	1.	1.
11	.00132	2.	2.	2.
12	.00671	1.	1.	3.
13	23.70000	2.	1.	1.
14	11.60000	2.	1.	3.
15	3.19000	2.	1.	3.
16	2.46000	2.	1.	1.
17	3.21000	2.	1.	1.
18	4.01000	2.	1.	1.
19	.03360	2.	1.	2.
20	16.40000	2.	1.	1.
21	.98000	1.	1.	3.
22	.62300	2.	1.	3.
23	3.20000	2.	1.	3.
24	.40900	2.	1.	1.
25	.60600	2.	1.	1.
26	.64100	2.	1.	1.
27	1.42000	2.	1.	1.
28	4.20000	2.	1.	1.
29	2.29000	2.	1.	1.
30	.25200	2.	1.	2.
31	.00427	2.	1.	1.
32	.00831	2.	1.	2.
33	.00197	2.	2.	2.
34	.00411	2.	2.	2.
35	.00011	1.	1.	3.
36	.00006	1.	1.	1.
37	.00113	1.	1.	1.
38	.00022	1.	1.	1.

	Failure Rate (%/1000 hrs.)	Temperature	Humidity	Vibration
39	.00308	1.	1.	1.
40	.00060	2.	3.	1.
41	.00078	1.	1.	1.
42	.01370	2.	1.	1.
43	.00687	1.	1.	1.
44	.00278	1.	1.	1.
45	.17200	2.	1.	3.
46	.02080	1.	1.	3.
47	.00228	2.	1.	2.
48	.00506	1.	1.	1.
49	.00495	1.	3.	2.
50	.02210	2.	1.	1.
51	.00412	1.	1.	1.
52	.21000	1.	1.	3.
53	.07800	2.	2.	2.
54	.04740	3.	1.	1.
55	.14800	3.	1.	3.
56	.02000	3.	3.	3.

Correlation Matrix:

	Temperature	Humidity	Vibration
Temperature	1	.40	.13
Humidity		1	.18
Vibration			1

Column Correlation Vector:

	Temperature	Humidity	Vibration
Failure Rate	.07	-.19	-.10

Regression Equation:

$$Y = 2.4 + 1.1 - 1.8H - .40V$$

Multiple Regression Coefficient:

$$R^2 = .07$$

F Test:

F Ratio = 1.2; $F_{.05}$ = 3.15 ∴ No Significance

Problem 2 - Resistance Welding Using Point Estimates

Measured Observations:

	Failure Rate (%/1000 HRS)	Temperature	Vibration	Mechanical Stress
1	.01220	2.	1.	1.
2	.00222	2.	1.	1.
3	.00286	2.	1.	1.
4	.28300	1.	1.	2.
5	.27400	1.	1.	2.
6	.82200	1.	1.	2.
7	.43700	1.	1.	2.
8	.52400	1.	1.	3.
9	.27900	1.	1.	3.
10	.23600	1.	1.	3.
11	.11700	1.	1.	3.
12	.00880	3.	3.	1.

Correlation Matrix:

	Temperature	Vibration	Mechanical Stress
Temperature	1	.75	-.80
Vibration		1	-.36
Mechanical Stress			1

Column Correlation Vector:

Failure Rate	-.66	-.30	.48

Regression Equation:

$Y = 1.09 - .61T + .31V - .17M$

Multiple Correlation Coefficient:

$R^2 = .59$

F Test:

F - Ratio = 3.8 $\quad F_{.05} = 4.07$

Problem 3 — Wire Wrap From Point Estimates

Measured Observations:

	Failure Rate	Temperature	Humidity
1	.0000007	1	1
2	15.2000000	2	3
3	2.6100000	2	3
4	.5220000	2	3

This problem failed to work on the computer because of singularity. By singularity, it is meant that the independent variables (temperature and humidity) were highly correlated. Therefore, a simple one factor regression was performed between failure rate and humidity. No significant relationship was found to exist between these two effects.

Problem 4 — Crimped Connections From Point Estimates

Measured Observations:

	Failure Rate (%/1000 hrs)	Temperature	Vibration
1	.00118	1	2
2	.00568	2	2
3	.00241	1	1
4	.00087	3	3
5	.01110	2	2

Correlation Matrix:

	Temperature	Vibration
Temperature	1	.84

Column Correlation Vector:

	Temperature	Vibration
Failure Rate	.11	-.13

Regression Equation:

$Y = 0.0066 + .0038T + .0046V$

Multiple Correlation Coefficient:

$R^2 = .17$

F - Test:

F Ratio = .21 $F_{05} = 19$

Problem 5 — Solder by Environment

Measured Observation:

	Failure Rate (%1000 HRS)	Vibration	Temperature	Humidity
1	.00032	1.	1.	1.
2	.11356	1.	2.	1.
3	.00056	1.	2.	3.
4	.00055	1.	3.	1.
5	.00044	2.	1.	1.
6	.00495	2.	1.	3.
7	.00316	2.	2.	1.
8	.01067	2.	2.	2.
9	.00158	2.	3.	2.
10	.00091	3.	1.	1.
11	4.17188	3.	2.	1.
12	.14765	3.	3.	1.

Correlation Matrix:

	Vibration	Temperature	Humidity
Vibration	1	-.012	-.22
Temperature		1	-.07
Humidity			1

Column Correlation Vector:

	Vibration	Temperature	Humidity
Failure Rate	.43	-049	-.21

Regression Equation:

$Y = -.69 + .62V + .069T - .18H$

Multiple Correlation Coefficient:

$R^2 = .21$

F Test:

F - Ratio = .70 $\quad F_{05} = 4.07$

Problem 6—Resistance Welding by Application

Measured Observations:

	Failure Rate (%/1000 HRS)	Temperature	Mechanical Stress
1	.03771	1.0157	1.7328
2	.00019	1.0153	1.0000
3	.00794	2.9026	1.0000
4	.00183	1.7620	1.0000

Correlation Matrix:

	Temperature	Mechanical Stress
Temperature	1	-.49

Column Correlation Vector:

	Temperature	Mechanical Stress
Failure Rate	-.32	.98

Regression Equation:

$Y = -.057 + .0042T + .052M$

Multiple Correlation Coefficient

$R^2 = .9985$

F Test:

F Ratio = 343.8 $F_{05} = 200$ ∴ Significant

t Tests:

$t_T = 4.89$

$t_m = 24.83$ $t_{.05} = 12.706$

Therefore Mechanical Stress is significant and temperature is not.

Problem 7—Solder by Application

Measured Observations:

	Failure Rates (%/1000 HRS)	Temperature	Humidity	Vibration
1	.02713	1.1628	1.0000	2.0704
2	.01029	2.0041	1.0000	1.0000
3	.00022	1.1672	1.1679	1.1669
4	.00040	1.2230	1.2230	1.2230
5	.00142	1.0497	1.0212	1.0540
6	.00360	2.2743	1.5806	2.2677
7	.00127	1.9982	2.9469	1.0653

Correlation Matrix:

	Temperature	Humidity	Vibration
Temperature	1	.52	.21
Humidity		1	-.11
Vibration			1

Column Correlation Vector:

	Temperature	Humidity	Vibration
Failure Rate	-.12	-.34	.51

Regression Equation:

$$Y = .00089 - .0024T - .0029H + .0095V$$

Multiple Correlation Coefficient:

$R^2 = .35$

F Test:

F - Ratio = .53 $\quad F_{.05} = 9.28$

APPENDIX V ESTIMATION OF FAILURE RATES, SAMPLE SIZES

The estimation of Failure Rates (i. e., the reciprocal of MTBF) for the various sources involved the observation of a random variable: the length of time a connection lived, say t. When there are N ≥ 1 failures the true failure rate is estimated by taking: $\dfrac{1}{\dfrac{\text{Total hours lived}}{n}}$. This is the "sample" failure rate which is used to estimate the true failure rate, and this is called a maximum likelihood estimator. It has a number of desirable properties, some of which will be mentioned but not defined. It is efficient, consistent, unbiased, and has minimum variance.

Now it often happens that in running a test or observing the operation of equipment, no failures occur before the test must be terminated. In this case the random variable t, (i. e., length of life) has not even been observed! In this case, speaking statistically, there is no valid point estimate available. A confidence interval estimate is available and the methods of computing it are well known.

Now, because of the fact that the failure rate cannot be a point estimate when N=0 (N=the number of failures) it often appears that data is being lost. One often hears the argument that if the device lasts x hours and the test is terminated before failure, surely something has been learned. This is absolutely correct. What has been learned is that there is a minimum value on true MTBF (i. e.: a lower confidence limit). None the less a point estimate (that has desirable properties) is not available. This should not be taken to mean that a point estimate cannot be had at all. For example, the number $\pi \cong 3.1416$ could be selected for an estimate and it would have variance 0 and would not even require a test. Unfortunately it also has properties which are very undesirable too. In any case this sort of thing has occurred in the connections study. A certain amount of data was obtained where no failures were observed. In reliability practice it has been often proposed that when this occurs (i. e., N=0) it should be assumed that N=1 and proceed as before. This procedure has the advantage of providing a point estimate for the failure rate which can be used for other computational purposes.

This procedure was not followed in this study even though a good deal of data was lost to the regression analysis because no failures were observed. The reasons why one failure was not assumed when none occurred are as follows: First:

The problem of the regression analysis was not just a matter of quantity of data but rather of quality of data. The assumption of one failure where none occurred would have increased the unexplained variation.

Secondly, and very important, the regression analysis required point estimates of failure rate which were unbiased so that the time functional relationships could be estimated. If, in case of no failures, N=1 had been used any results obtained from the regression analysis would have been very difficult to interpret in mathematical terms. The estimation of failure rate using N=1 is biased when 0 failures were observed.